OMNIDIRECTIONAL 3D PRINTING OF METAL MICRO-ARCHITECTURES VIA DROPLET SLIDING OVER CURVED SURFACES

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Abstract

As a simple, fast, and green 3D printing method, droplet-based manufacturing is suitable to print various materials to manufacture structures. However, up to now, it has hardly been capable of manufacturing omnidirectional designs with slender horizontal or upside-down sections, since the required rotation of the nozzle or workpiece negatively affects printing performance. Here, we employed a novel slide-guided droplet deposition method for printing parts with arbitrary-angle overhangs up to 180°. Arc-shaped slides with metallophobic surfaces are used to smoothly deflect droplets and provide a full control of droplets’ impact angle onto the workpiece. We show that gently curved impact surfaces prevent droplet bouncing, and quantitatively describe the transition from sliding to bouncing by measurements, simulations, and theory that predict our process window. Furthermore, the temperature of the slides is controlled to modify the temperature of droplets after they leave the generator, enabling fabrication of horizontal pillars with locally tunable morphology and optimization of drop-to-drop adhesion. The versatility of the slide-guided deposition is highlighted by fabricating structures with high aspect ratios and free-standing branches in arbitrary angles including hung sections where droplets are deposited from a fully reversed direction. Since the proposed slide-guided deposition uniquely facilitates fabrication of slender metal structures from arbitrary angles without rotating the workpiece or nozzle, it helps advance the development of many other research fields, such as antennas, branch-like heat sinks, and metal micro-lattices, where complex structures are needed.

Introduction

Precise drop-on-demand printing is a low-cost, contactless, and environmentally friendly 3D printing technology. Droplets of wax, solder, aluminium, gold, copper, and nano-particle suspension formulation have been utilized to print structures with thin-walls and high aspect ratios. Already, thin horizontal lines, vertical and inclined pillars, slender walls, and programmable 3D shapes have been demonstrated to illustrate the droplet printing ability. However, up to now, building parts with overhangs without support is still exceedingly complex, since droplets deposited from a nozzle are typically aligned with gravity and can only be stacked up to a ~40° angle. Changing the impact angle by rotating the nozzle is far from trivial, since current droplet ejection methods are sensitive to acceleration (gravitational or rotational acceleration). Rotating the nozzle of high-temperature setups with large, heavy, and complex cooling systems used in metal printing is virtually impossible. Rotating the workpiece with a multi-degree-of-freedom (DOF) motion platform will result in plastic or elastic deformation of soft or slender structures, and thus inaccurate deposition locations. Therefore, making slender metal structures is still challenging, especially for t-junctions or branching structures such as antennas, branch-like heat sinks, and metal micro-lattices. Alternative techniques can achieve omnidirectionality, but they lack the ability to print metals with a density higher than 95%, require curing, and are limited to pure metals.
Figure 1. The principle of the slide-guided droplet deposition. (a) Schematic diagram of the metal droplet printing system. Metal droplets are ejected from the printing system (top). The liquid metal is shown in red. The arc-shaped slide controls the droplet deposition direction, in this case, to horizontally impact the workpiece. (b) and (c) Printing inclined pillars by using sliding deposition with deflection angles less and larger than 90°, respectively.

Here we demonstrate that changing the direction of droplets after ejection enables their impact at arbitrary angles onto the workpiece. The key concept is to impact droplets onto a curved surface that guides them until their final direction is reached, as shown in Fig. 1(a). As the slide surface is metallophobic, the droplets slide rather than roll over its surface, as discussed in supplementary note 2. The droplets are deposited onto the workpiece at an angle θ, as controlled by the slide angle (Fig. 1(b), (c)). Droplet bouncing easily occurs in this configuration, but is prevented in the operating window that we predict in the following. Subsequently, we demonstrate that the slide temperature controls the bonding and micro-architecture of the resulting pillar. Finally, we highlight the versatility of slide-guided deposition by fabricating branched metal architectures with spanning features and overhangs at arbitrary angles.

Figure 2. Experiments, theory, and modelling results that identify sliding or bouncing regimes for droplet motion along the slide. (a-c) High-speed photographs (grayscale images) and corresponding numerical simulations (colour images) at times as indicated; the curved surface at the left of each image indicates the slide. (a) Droplet slides smoothly along the slide. (b) Droplet impacts and bounces off from the slide. (c) Droplet impacts and bounces off from the low section of the slide. (d) Schematic diagram of droplet impact model. Droplet impacts on the fillet section and the arc section are both illustrated. The droplet at the maximum recoil instant is also shown on the lower part of the arc guide. (e) Critical surfaces of the droplet bouncing off from the slide. Those surfaces are predicted by equations (1) and (2), respectively. The horizontal plane illustrates the location of the cross-section in (f). (f) Dimensionless phase diagram of the impact regime as a function of x_{impact} and We, which is the cross-section shown in (e). The markers indicate numerical simulations. Red circles represent droplets moving along slide surface. Green crosses indicate droplets bouncing off; Solid lines indicate the theoretically modelled separation between the bouncing and sliding regimes. The horizontal bar illustrates the experimental parameter region in g. (g) Experimental results of probability (P) of droplets moving along slide surface or bouncing off with different values of the impact offset (x_{impact}). The grey rectangle represents the simulated range of x_{impact} for achieving the along-surface motion for We=0.5, r_{d}*=0.054. Its gradual edges indicate the numerically-obtained threshold area between the bounce and the along-surface motion regime.

Droplets smoothly slide downward if they impact on the vertical part of the guide that is tangential to their initial ejection direction from the nozzle, as shown in Fig. 2(a). As shown in the high-speed droplet images in Fig. 2(a), the droplet maintains a nearly spherical shape during impact. In contrast, if they impact on a surface with small inclinations as observed at the top (Fig. 2(b)) or bottom (Fig. 2(c))
sections of the slide, they bounce off and the control over their trajectory is lost. In those cases, the droplets flatten first and then recoil from the slide.

We model the transitions between the bouncing and smooth sliding regimes by describing the droplet with the Kelvin-Voigt model\(^{25}\), see supplementary note 3A. A droplet is described by two masses, indicated as \(m\) in Fig. 2(d), linked by a spring with spring constant \(k\). The influence of viscosity (damping) is compared to surface tension (elasticity by surface minimization) by the Ohnesorge number \(\text{Oh} = \mu/(\rho D_d)\), with viscosity \(\mu = 1.35 \text{ mPa} \cdot \text{s}\), surface tension \(\sigma = 0.49 \text{ N} \cdot \text{m}^{-1}\), and metal density \(\rho = 7800 \text{ kg} \cdot \text{m}^{-3}\) for liquid tin at a temperature \(T = 576 \text{ K}\). Since \(\text{Oh} \approx 0.0012 < 1\), viscous dissipation is ignored. The Weber number \(\text{We} = (\nu D_d^2)/\sigma \approx 0.5\), with the droplet velocity \(\nu_d\) is approximated to be \(1 \text{ m} \cdot \text{s}^{-1}\), indicating that inertial and surface energies are comparable and should both be included in the model. The Bond number \(\text{Bo} = (\nu D_d^2)/\sigma \approx 0.01 \ll 1\), indicating that the gravity can be ignored in the analysis as compared to inertia.

Based on Fig. 2(a-c), we assume that droplet bouncing originates from relaxation of the oblate drop shape observed in Fig. 2(b) (3rd image) or Fig. 2(c) (4th image). Bouncing is counteracted by the centrifugal force and gravity pressing a droplet against the wall, thus promoting sliding behaviour. Therefore, in supplementary note 3A, the droplet dynamics are modelled for two distinct zones \(x_{\text{impact}} < r_d\) (Fig. 2(b)) and \(x_{\text{impact}} > r_d\) (Fig. 2(a), (c)), in which the deformation of a droplet as a function of \(x_{\text{impact}}\) depends on the local curvature of the slide. This approach provides two critical conditions beyond which the droplet bounces. The regime for droplet sliding is obtained by re-writing equation. S(10), yielding equations. (1) and (2), also shown by equation. S(11) and S(12) in Supplementary note 3A.

\[
\begin{align*}
\text{We} &> \left(\frac{\nu \xi_s \sin \alpha_1 - 2 \pi^2 r_d^* Bo \sqrt{1 - \xi_s \sin^2 \alpha_1}}{r_d^* \sqrt{\pi (1 - \xi_s \sin^2 \alpha_1)}}\right)^2, & \text{sin } \alpha_1 = \frac{\sqrt{(1 - \xi_s r_d^*)^2 - (1 - x_{\text{impact}}^*)^2}}{1 - \xi_s r_d^*}, & \text{for } x_{\text{impact}}^* \geq r_d^*, (1) \\
\text{We} &> \left(\frac{\nu \xi_s \sin \alpha_2 - 2 \pi^2 r_d^* Bo \sqrt{1 - \xi_s \sin^2 \alpha_2}}{r_d^* \sqrt{\pi (1 - \xi_s \sin^2 \alpha_2)}}\right)^2, & \text{sin } \alpha_2 = \frac{\sqrt{(1 + n \xi_s r_d^*)^2 - (1 + n x_{\text{impact}}^*)^2}}{1 + n \xi_s r_d^*}, & \text{for } x_{\text{impact}}^* < r_d^*, (2)
\end{align*}
\]

where \(r_d^* = r_d/\rho_s\) is the nondimensional droplet size with the slide radius of 1 mm, \(x_{\text{impact}}^* = x_{\text{impact}}/r_s\) is the nondimensional impact offset, and \(n = r_f/r_s\) is the ratio of the arc slide radius \(r_s\) to the fillet radius \(r_f\).

**Figure 2(e)** shows the two critical surfaces that result from equations (1) and (2), separating the bouncing and sliding regimes. Parameter combinations above or between those surfaces imply that a droplet will move along the arc slide. Note that for large \(\text{We}\) numbers, high tangential velocities result in a large centrifugal force that pushes the droplet against the slide surface. 3D simulations of droplet impact on a curved surface were done to further study the droplet impact dynamics under different parameter combinations of \(\text{We}\) and \(x_{\text{impact}}\) (For details, please refer to supplementary note 4). Fig. 2(a)-(c) show that the droplet shape and bouncing behaviour qualitatively agree with the measurements. With the numerical model, a phase diagram that indicates sliding or bouncing as a function of \(x_{\text{impact}}\) and \(\text{We}\) map was
made as shown in Fig. 2(f). The simulated transitions between bouncing and sliding are in excellent agreement with the above-presented theoretical model (indicated as coloured lines). Based on the simulated thresholds of the critical $x_{\text{impact}}^* = 0.045$ and 0.0584 at $We = 0.05$, the fitting parameters, $\xi_1 = 1.087$, $\xi_2 = 0.913$, $\varsigma_1 = 4$, and $\varsigma_2 = 0.34$, are obtained. The parameters of $\xi_1$ and $\xi_2$ are used to accommodate slightly non-axisymmetric droplet deformation and are expected to be close to 1. The dimensionless parameters, $\varsigma_1$ and $\varsigma_2$, indicate the amount of kinetic energy being transformed into potential energy in fillet and slide section respectively. The larger values of these parameters are, the more energy is involved in the transformation, see supplementary note 3A. With $x_{\text{impact}}^*$ close to one droplet radius, sliding motion is achieved for a wide range of $We$ numbers (~0.5 to 100). At high impact $We$ numbers, droplets move along the guide for a wider $x_{\text{impact}}^*$ range. For example, for $10 \lesssim We \lesssim 100$, the along-slide motion of droplets is observed for $x_{\text{impact}}^*$ ranging from 130 $\mu$m to 190 $\mu$m which is experimentally easy to achieve.

Series of impact experiments with solder droplets were conducted to validate the sliding or bouncing regimes as a function of $x_{\text{impact}}^*$. The probability $P$ of droplets moving along slide for different values of $x_{\text{impact}}^*$ is shown in Fig. 2(g). In our test, droplets with the radius of 161 $\mu$m were ejected at a velocity of 0.3 m/s onto a 3 mm-radius slide. The experimental results indicate that there is a process window for droplets sliding on the slide. Our theory recovers these results, predicting sliding for $0.043 < x_{\text{impact}}^* < 0.057$ (corresponding to $x_{\text{impact}}$ of 130 $\mu$m to 170 $\mu$m, respectively) as shown by the blue and red lines in Fig. 2(f). These experimentally obtained sliding regime validates both the theoretical and numerical results, highlighting the controllability and predictability of slide-based droplet guiding.

Figure 3. Droplets are deposited on different temperature slides. (a) By contacting with a cold slide, metal droplets are easy to stop on the cold slide due to the local stick. (b) Pinned droplets hinder the sequential along-slide motion, resulting in a short-curved pillar on the slide. (c), (e), and (g) are horizontal overhanging pillars which are printed with a slide temperature of 200 °C, 300 °C, and 400 °C, respectively. (d), (f), and (h) are enlarged views of the corresponding overhanging pillar tips. The small schematic diagrams on the left illustrate the droplet temperature varies after they move along different temperature slides.

Beyond controlling the droplet flight direction, the metal slide is an effective tool to change the droplet temperature. To test the effect of the slide temperature on metal droplet printing, droplets with an initial temperature of 300 °C were deflected by the slide held at temperatures of 50 °C, 200 °C, and 400 °C. At 50 °C, molten tin droplets can be observed to stick to the slide surface, as shown by the third image of the high-speed serial images in Fig. 3(a). In the stick case, a droplet is first stuck to the contact area and then slides down under the action of the inertial force. In other cases, droplets may pile up (Fig. 3(b)) or bounce away due to the collision of subsequently coming droplets, inhibiting the possibility for slide-guided printing.
At higher temperatures, droplets were smoothly deflected to a horizontal trajectory, yielding horizontal overhanging pillars on the side of vertical pillars. The influence of the slide temperature was assessed by comparing the beaded morphology of the resulting pillars. At $T = 200^\circ C$, the pillar exhibits a beaded surface morphology (Fig. 3(c), (d)). The spacing between these beads is known to depend on the initial droplet temperature$^{15}$, and was measured to be 0.28mm based on ten measurements along the centre axis. The joints formed by these low-temperature-slide guided droplets are quite weak. The pillar easily fell off from the vertical one with a light touch. Here, both the rough morphology and the weak joint indicate that droplets were insufficiently heated for strong bonding to the workpiece$^{26}$.

When the slide temperature was increased to 300 $^\circ C$, a beaded morphology with a distance 0.22 mm between the droplets was observed (Fig. 3(e), (f)). This reduced distance indicates that droplets melt deeper into the solid pillar, which indeed could withstand touch or motion of the workpiece. The beaded morphology is close to that of vertical pillars printed without the slide (with period 0.2 mm), suggesting that the droplet temperature at this test is maintained by the slide.

If the slide temperature was increased to 400 $^\circ C$, droplets formed a smooth surface at the tip of the horizontal pillar, as shown in Fig. 3(g), (h). Here, control was lost over the thickness of the pillar so this regime is less useful for the current material and process parameters.

Together, these results convincingly show that the slide guide disconnects the droplet ejection temperature from its deposition temperature. To estimate the droplet temperature change by the slide, three timescales are calculated and compared here, which are the droplet thermal diffusion time scale $\tau_d$, the delay time scale $\tau_r$ caused by the thermal resistance, and the contact time $\tau_c$ (For details, see supplementary note 3B). When droplets with $r_d = 161 \ \mu m$, $u_d = 0.3 \ m \ s^{-1}$, and an initial temperature of 300 $^\circ C$ impact on the slide with radius $r_s = 3 \ mm$, $\tau_d \sim 10^{-3} \ s$, and $\tau_r \sim 10^{-5} \ s$. The contact time $\tau_c$ for a droplet moving on a quarter slide is approximately 0.0156 s, sufficient to change the droplet temperature by thermal conduction and diffusion. Since high-temperature droplet ejection is still very challenging$^{15,23}$, on-the-fly processing by slide-guided deposition is a promising strategy for improved process control at high temperatures. For example, stable ejection of small aluminium or magnesium droplets with elevated temperature is challenging since molten aluminium or magnesium liquids are chemically active at high temperatures and therefore easily damage the nozzle. Controlled heating of these droplets via hot slides may therefore improve the droplets’ metallurgical bonding to the workpiece.

Figure 4. Printing of various shape structures by utilizing slide assisted deposition. (a) Deposition of solder droplets with a quarter-circle slide. (b) Droplet flying direction is reversed by using a half-circle guide. (c) Deflection of solder droplets with a deflection angle of 140$^\circ$. (d), (e), and (f) are structures with titled overhanging pillars, which are manufactured by coordinating the x-and z-axis motion with a step of 0.12mm, 0.15mm, and 0.2mm, respectively. (g) Comparison of our method to others reported in literature on maximum printing angles. (h) Mechanical test of a free-standing pillar. The colour scale indicates
modelled deformation. (i) and (j) are small antenna-like structures demonstrating that omnidirectional slender pillars can be printed at arbitrary places.

To assess the versatility of the slide-guided droplet deposition, slender structures were constructed at arbitrary angles and places. Droplets deflections are done by using slides in different circumferences. A quarter-circle slide placed down the nozzle deflect droplets by $90^\circ$ to print horizontal pillars (Fig. 4(a)). A half-circle slide is used to reverse the droplet deposition direction (Fig. 4(b)), which allows printing of structures upside down. With a three-quarter slide, droplet deflection angles can be reversed (Fig. 4(c)), showing a stable control of droplet deflection. The angle of the printed pillars could also be tuned by coordinating the $x$-axis and $z$-axis of the printhead. As shown in Fig. 4(d)~(f), pillars with angles ranging from $124^\circ < \theta < 151^\circ$, are achieved by setting the motion step between 0.12 and 0.2 mm as indicated. The tilted angle was changed gradually, demonstrating flexible adjustment of the inclined angle without changing the slide. Our previous work shows that a $43^\circ$ range of angles can be achieved in this fashion$^{15,19}$. Therefore, we expect that 3 slides are enough to enable printing of slender structures with arbitrary angles.

To our best knowledge, we achieved droplet-based printing of slender metal structures at arbitrary angles for the first time. Fig. 4(g) shows the inclination range of constructs made with alternative droplet-based strategies. Laser-induced Forward Transfer enabled fabrication of inclined gold$^{19}$ and copper$^{10}$ pillars with angles up to approximately $30^\circ$. Pneumatic pressure-based printing of aluminium droplets yielded titled angles up to $40^\circ$$^{15}$. Piezoelectric generation of gold nanoparticle suspension droplets produced inclined pillars with angles up to $45^\circ$, which could be extended up to $50^\circ$ by using E-jet to print Ag, Cu, and Co pillars$^{12}$. Wax pillars with an tilted angle of up to $85^\circ$ can be printed by using a piezoelectric generator under conditions when new coming droplets could almost fully coalesced into previous deposited and solidified droplets$^{4}$. In-situ photopolymerization of air-filled droplets at their impact location yielded angles up to $90^\circ$$^{27}$. We demonstrated direct deposition of overhanging structures with smoothly-tuneable inclined angles ranging from $0^\circ$ up to $180^\circ$ at high aspect ratios larger than 10, demonstrating a significant advantage over other direct deposition methods.

To test the strength of the joint and mechanical properties of printed pillars, a downward force is applied at the tip of the horizontal structures, as shown in Fig. 4(h)$^{28}$. The shape of the deformed pillar agrees well with the plastic deformation simulation with uniform diameters, demonstrating that the uniform thickness and the equal bonding strength of each droplets. Additionally, we hung weights at the tip of the horizontal section to qualitatively test the stiffness of the printed pillars. The 0.031 g pillar bears 0.53 g objects without obvious deformation, as shown in supplementary note 6. That is almost 17 times its own weight, indicating that the printed structure is quite strong.

Remarkably, we printed several antenna-like slender structures by combining quarter- and half-circle slides, as shown in Fig. 4(j). The printed structures are ~24 mm high and have four horizontal overhanging arms, with lengths of approximately 18 mm. Four arms were deposited onto a single
location on the vertical pillar without melting it down, demonstrating the advance of the precise control of the mass flow and heating. In Fig. 4(i), two small pillars were also printed on each arm. The outside pillars have a height of 6 mm and the inside ones are about 3 mm high. The arms did not significantly deform during the printing process, demonstrating the ability to form weak-stiffness parts via droplet sliding deposition.

In Fig. 4(j), the upside-down sections were first printed at one side of the horizontal arms. Then, the slender structures were continuously printed on the upside-down pillars to form an open square structure. This test demonstrates the ability of printing structures in the anti-gravity direction. Looking closely at the pillars printed in different directions, we can readily observe that the morphology of upside-down pillars is obviously different for the horizontally and direct printed pillars, as illustrated by enlarged views in supplementary note 5. For the upside-down deposition, the average distance between two adjacent interfaces is 0.35 mm, which is slightly larger than the interface distance 0.2 mm on the pillar deposited without using a slide. Since the Bond number \( \text{Bo} \approx 10^{-2} \ll 1 \), the effect of gravity can be reasonably ignored. Instead, the impact velocity may have been reduced by the conversion of kinetic energy into gravitational potential energy (e.g., droplets, with 0.31 mm diameter and initial velocity of 0.3 m/s, rise only 4.5 mm after all the kinetic energy transfers the gravitational potential energy), limiting the deformation and contact area between droplets.

**Discussion**

In summary, a novel slide-guided deposition method is proposed to print overhanging structures. Molten metal droplets smoothly move along the slide surface and eventually land on desired locations. The direction of deposition is coarsely customized by altering the inclined angle of the arc slide outlet, and fine-tuned by spatial translation of the slide. Bouncing of droplets upon impact is prevented by the curvature of the slide. The transition between sliding and bouncing is theoretically and numerically modelled, and experimentally validated, resulting in quantitatively predictable control parameters that prevent bouncing.

Utilizing the proposed method enables direct-printing of pillars with arbitrary angles up to 180° and aspect ratios larger than 10. In particular, free-standing branch structures were printed by combining top-down, horizontal, and upside-down printing approaches, demonstrating a significant step towards 3D printing of complex structures with droplet-based methods.

**Methods**

*Metal droplet generator*

The metal droplet generator, mentioned in our previous work, was used to eject small mono-sized metal droplets. A piezoelectric actuator, located inside a cooling water case, is used to generate vibration pulses. A metal rod, with one end immersed into liquid metal and the other end connected to a
piezoelectric actuator, is utilized to transfer vibration pulses into the metal liquid. This rod also insulates the piezo-actuator from high crucible temperature. A stainless crucible, heated by an external electric heater, is assembled down to the cooling case and has a small orifice of 300 μm diameter at its bottom centre. In our experiment, the solder is heated up and maintained its temperature at 300 °C during droplet ejection.

**Arc-shaped slide**

The 304 stainless steel is chosen to fabricate the slide. A nano-meter thick chromium oxide layer exists on the stainless-steel surface to prevent the contact between molten metal droplets and the metal surface. Such oxide skin is feasible in bearing molten metal droplets impacting and sliding since this skin is refractory and heal quickly after being damaged. The surface of slide has a roughness of Ra 0.2 μm and a 1 mm diameter fillet, forming the smooth guide inlet (Fig. 1(a)). The guide is attached to a guide supporter, which can be moved horizontally by a manual platform. The slide can be heated up to 400 °C by a heater inside the supporter to avoid the droplets from sticking onto the slides during solidification. By using different slides, pillars with inclined angles, equal to, smaller than, and larger than 90°, can be obtained, as shown in **Fig. 1(a)**, (b), and (c), respectively. Furthermore, overhangs can be printed on one side of the vertical pillar distancing from the pillar top by changing the outlet location of the slide.

The droplet generator and the guide are both localized in a low oxygen environment. This environment is maintained by a glovebox, in which the gas is circulated through an oxygen-removing column to obtain a high-purity argon gas atmosphere.

**Motion platform**

The coordinate system is also illustrated in **Fig. 1(a)**. The x- and z-axes are both set to be tangent to the arc slide, which intersect at lower left down to the slide. The deflection angle of the deposited droplets, notating as θ, is measured clockwise from the downward direction (minus z-axis). The impact offset of the droplet, notating as x_{impact}, is the x coordinate of the droplet centre at impact.

**Characterization**

Both the stroboscopic photography system and the high-frame photography system are utilized to record droplet images. The stroboscopic photography system consists of a light barrier, a delay unit, a flash lamp (DB Plus Digital, Nova-Strobe, US), a global shutter camera (UP-610, Uniq, US), and long-distance microscope (LDM K2 Distamax, Infinity Photo-Optical Company, US). The light barrier consists of a laser, a lens, and an optical detector. The laser beam orthogonally crosses the droplet pass way and is focused into a spot of one droplet diameter at the crossing point. When a metal droplet passes through the laser beam, it shields the laser beam and then activates the optical sensor to generate an electric pulse which triggers the camera and the flash lamp in sequence to capture a picture of moving droplets.
The high-speed photography system consists of a high-speed camera, the long-distance microscope, and a high-power light source. The high-speed camera (The i-speed 220, iX Cameras, UK) has the maximum frame rate of 600 fps at full resolution (1600 x 1600 pixels) and 204100 fps at reducing resolution (128x10 pixels).

In addition, droplet-shape analysis software, ImageJ with the DropletSnake plug-in, is utilized to measure the droplet contact angles, which is obtained by the piecewise polynomial fitting of the droplet profile. The final printed structures are visualized using a scanning electron microscope (VEGA 3 LMU, Tescan).

**Declarations**

**Author Contributions**

**Jun Luo** designed the study, refining the ideas, performed the data analyses, and wrote the manuscript;

**Jingyuan Cheng** updated the slide-guided system and performed the branch structure printing experiment;

**Yacong Dong** designed and manufactured the slides, and he also performed droplets sliding experiment;

**Lehua Qi** contributed to the main conception of the study;

**Ni Li** helped perform the analysis with constructive discussions;

**Claas Willem Visser** contributed significantly to analysis and manuscript preparation.

**Conflicts of interest**

There are no conflicts to declare.

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