

Liquid lace: Regular pattern formation by under-extrusion

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Fused filament fabrication (FFF) is a common technique in additive manufacturing. In this methodology, thermoplastic filament is melted and extruded through a nozzle, depositing a highly viscous thread that rapidly cools—a feature essential for printing in sequential, vertical layers that become three-dimensional objects [1]. Here, we focus on the emergence of periodic patterns when molten filament material is extruded too slowly in this process. Under-extrusion is often considered

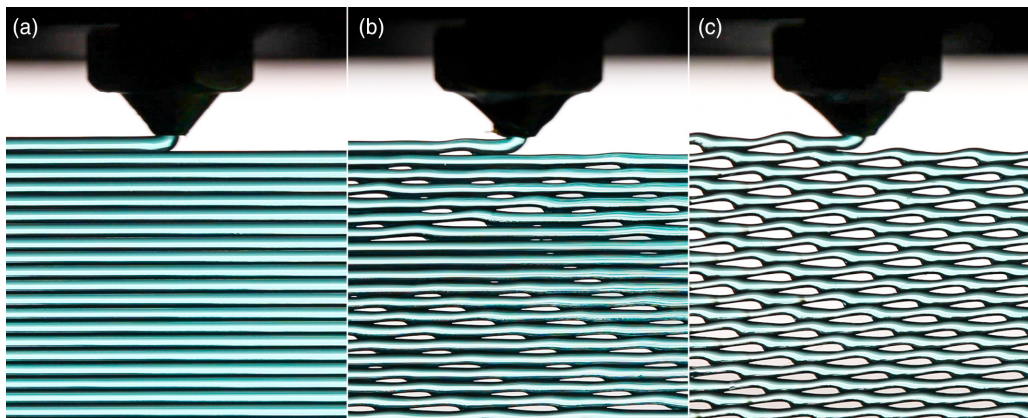


FIG. 1. Video stills showing molten polymer (copolyester—Fillamentum Lagoon Transparent) deposited in layers by a 1-mm nozzle moving in a straight line (Prusa i3 MK3S+, nozzle temperature $T \simeq 260^\circ\text{C}$ and bed temperature $T \simeq 75^\circ\text{C}$). (a) Print where layers are extruded with a flow rate sufficient to create a solid wall (extrusion multiplier, $e = 1$). [(b), (c)] Layers printed with flow rates sequentially reduced, i.e., intentional under-extrusion is enhanced from (b) ($e = 0.6$) to (c) ($e = 0.5$). See <https://doi.org/10.1103/APS.DFD.2023.GFM.V0087>.

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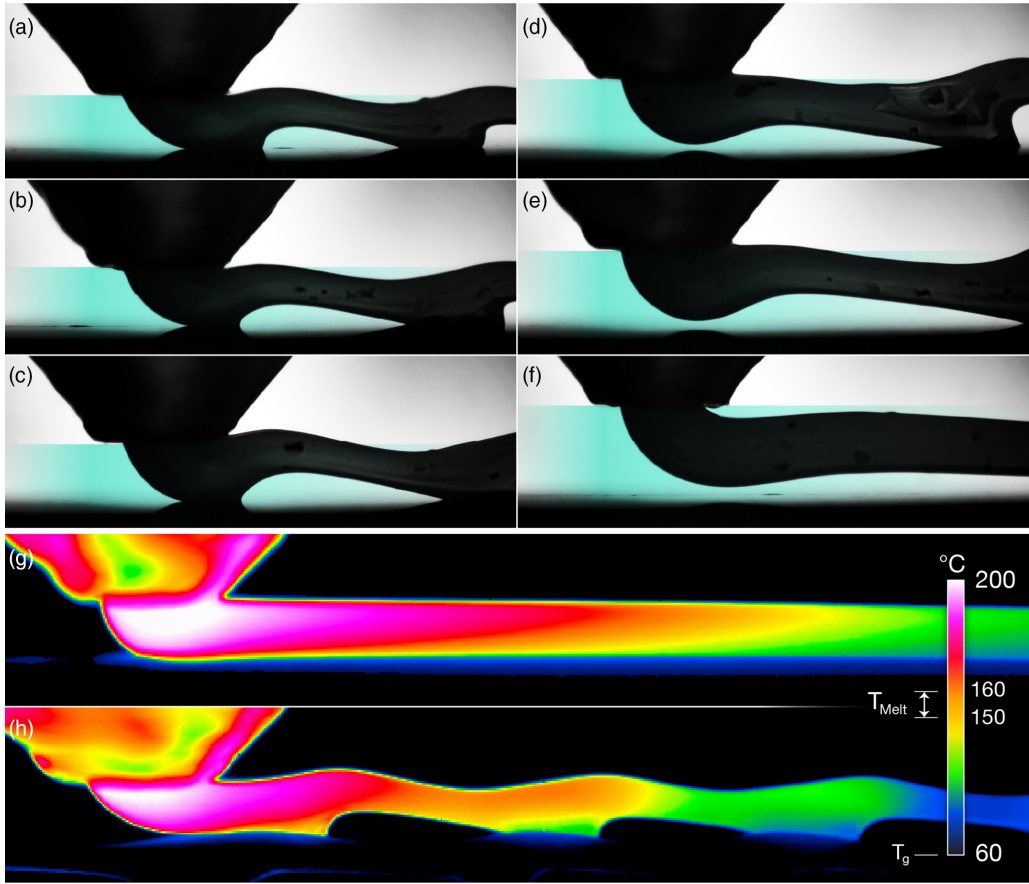


FIG. 2. Video stills of molten filament (polylactic acid) extruded from a 1-mm nozzle (nozzle temperature $T \simeq 215^\circ\text{C}$ and bed temperature $T \simeq 60^\circ\text{C}$). The videos are recorded from the nozzle frame-of-reference, with the substrate moving left to right. [(a)–(f)] Flow rates are held constant while the gap between the nozzle and substrate (illustrated in blue) is sequentially increased until the filament no longer makes contact. [(g), (h)] High-speed thermal video frames (Infratec ImageIR) for a solid extrusion [(g), $e = 1$] and under-extrusion [(h), $e = 0.4$]. See <https://doi.org/10.1103/APS.DFD.2023.GFM.V0087>.

a defect in FFF printing, typically caused by nozzle clogs, filament jams, and other issues that prevent adequate filament flow through the nozzle [2]. However, intentionally under-extruding recasts the instability as a robust manufacturing technique [3,4] for efficiently fabricating porous materials without formwork, advanced tooling, or complicated machine control, e.g., for the assembly of textiles [5].

In Fig. 1, we present images showcasing the onset of pattern formation. By reducing the flow rate of molten filament below a critical value, the extrudate transitions from a solid, adhered thread (a) to a pattern consisting of an adhered region followed by a narrow, unadhered thread (b). Reducing the flow rate further results in a regular pattern (c). The images also show that the pattern is self-stabilizing, where geometric features from the previous row contribute to the stability around a natural wavelength. In Fig. 2, we present high-speed video frames of the instability. In (a)–(f), the pattern forms on a flat substrate positioned at increasing distances from the nozzle, noting the evolution of wavelength and amplitude as the polymer touches, sticks, and stretches.

In closing, we note that this pattern complements the rich library of thread-mediated instabilities, including the classic Rayleigh-Plateau instability [6], the breakup of successively printed jets [7,8],

the pearling and arching of granular suspensions [9], and the coiling of viscous and elastic threads [10]. In the case of FFF, we anticipate that the details of pattern formation hinge on a subtle interplay between hydrodynamics, rheology, and cooling [11], as seen in the thermal images in Figs. 2(g) and 2(h).

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