

Viscoelastic fluids with no strings attached

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INSACO INC. has the ability to grind and polish almost any geometric feature in glass, ceramic, and sapphire!

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If you've ever wielded a glue gun, you likely dealt with the wisps of glue that trailed after it. The same issue plagues additive manufacturing: Instead of a tidy reproduction of the desired shape, a three-dimensional printer constructs an object marred by plastic strings, as shown in figure 1. Those strings are difficult to prevent when dispensing plastics, polymers, and other viscoelastic fluids, which behave as viscous fluids at low speeds and as elastic solids at high speeds.

When an ordinary Newtonian fluid such as water is dispensed from above, it bridges the gap between the target substrate and the nozzle. If the gap is kept below a critical value, the connection is stable. At or above that value, gravity gradually drains the liquid until the bridge breaks. To speed up the severance, one can simply lift the nozzle to thin the bridge until it splits.

Retraction also expedites the breakup of viscoelastic liquid bridges. But as the bridge is elongated, the liquid becomes more elastic and harder to break. Once the connection snaps, elongated strands and droplets, shown in figure 2a, can fall in unpredictable and potentially troublesome ways. For example, in the process of gluing electronic components on printed circuit boards, a stray string of glue can ruin the device. In short, there's a tradeoff between dispensing quickly and dispensing cleanly.

Now Amy Shen and Simon Haward, of Okinawa Institute of Science and Technology Graduate University in Japan, and their colleagues have developed a new rotation-based method to dispense viscoelastic fluids. Their high-speed video analysis and viscoelastic-flow simulations show that twisting the fluid bridge, rather than stretching it, quickly breaks the connection without producing strings.¹

A new twist

The problem of how to efficiently dispense viscoelastic fluids first came to the attention of Hammad Faizi, a co-lead author on the study, in 2015. An undergraduate at the University of Hong Kong at

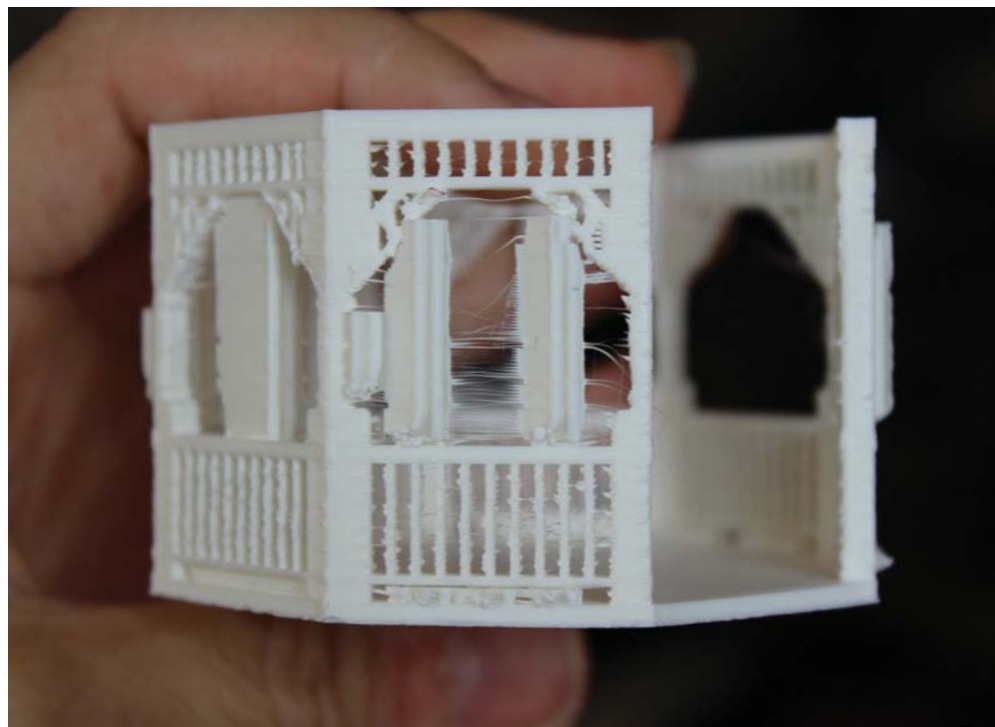


FIGURE 1. PLASTIC STRINGS mar the 3D-printed gazebo shown here. The strings appear when the printer nozzle lifts to detach from the deposited viscoelastic fluid. That retraction elongates the connecting fluid bridge, and after detachment, the strand sticks out. (Photo by Vicky Somma, CC BY-NC-SA 2.0.)

the time, he learned about the issue in a summer internship with ASM Pacific Technology, a company that specializes in designing and manufacturing semiconductor technology. When Faizi returned to school, he and fellow undergraduate San To Chan delved into the problem under the supervision of Anderson Shum. They found that rotating the dispensing nozzle yielded cleaner and faster application, a discovery that led to a patent application and their undergraduate dissertations. But they couldn't explain the underlying physics.

To pursue his PhD, Chan joined Shen's group, which specializes in the rheology of viscoelastic fluids. And in 2019 Shen, Chan, and their colleagues resumed investigating the effects of rotation on fluids. Chan built a simple experimental setup composed of two plates: an upper plate that can rotate and a lower plate that can move vertically to set the distance separating them. The researchers sandwiched 40 μL of liquid between the plates, separated by 2 to 4 mm, to form the ex-

pected liquid bridge with a radius on the order of a millimeter. They tested four viscoelastic silicone oils with different viscosities and, for comparison, a Newtonian fluid called Infineum S1054.

At various plate separations and rotation speeds, Shen and her group members filmed the fluid to track the bridge's radius as a function of time and analyzed the data with a program written by Faizi. They found that as both silicone and Infineum are twisted, the top half of the fluid rotates like a solid object, and the lower half is nearly stationary. So the twisting localizes at the neck where the top and bottom halves meet, similar to that of a washcloth being wrung out, and pinches off the liquid bridge. When the plate rotates at 35.3 Hz, Infineum takes about 9 s to break, compared with about 60 s with no rotation. The silicone bridge also breaks faster under rotation—in fact, even an otherwise stable bridge snaps apart in around 1 s. But instead of the broad concave form of the Infineum bridge, the thinning silicone bridge has a

peculiar narrow indentation on its sides.

The dynamics of viscoelastic bridges depends on a balance of inertial, elastic, capillary, and gravitational stresses and a host of parameters that includes density, surface tension, viscosity, elasticity, plate separation, and rotation rate. But surprisingly, the results are straightforward: The silicone bridge radius decreases with time t according to the power law $R \propto t^{-\beta}$, where β depends on a single dimensionless parameter, the Tanner number, which characterizes the relative importance of the torsion-induced elastic stresses compared with capillary stresses. The Tanner number is similar to the Reynolds number, which characterizes the relative importance of viscous and inertial forces.

As the viscoelastic bridge is twisted, the shear stresses at the neck generate stresses perpendicular to the fluid's surface, which doesn't happen in ordinary Newtonian fluids. Those shear-induced normal stresses overcome surface tension to form an indentation in the side of the bridge that's tenths of a millimeter wide. The indentation further localizes the shear stress and thus further increases the normal forces, which draw the indentation toward the middle of the bridge. That feedback loop results in the indentation propagating inward until the upper and lower halves of the liquid are separated, without any stray strands, as shown in figure 2b.

Because the indentation splits an otherwise stable liquid bridge, gravity can't be the source of the behavior. And given that the Newtonian fluid doesn't form an indentation, the behavior must be related to an elastic effect. So Shen and her colleagues hunted for an elastic instability that could explain their observations.

On the edge

Chan noticed that the indentation behavior resembles a flow instability first reported in 1963: edge fracture.² In that phenomenon—which emerges in various viscoelastic fluids, including toothpaste—shearing above a critical rate induces a sudden indentation, which localizes the shear stress and invades the fluid.

Edge fracture looks similar to what Shen and her group observed, but the phenomenon was previously investigated in a regime where the radius of the fluid was an order of magnitude larger than the height. Could the same behavior occur in their liquid bridge, with its

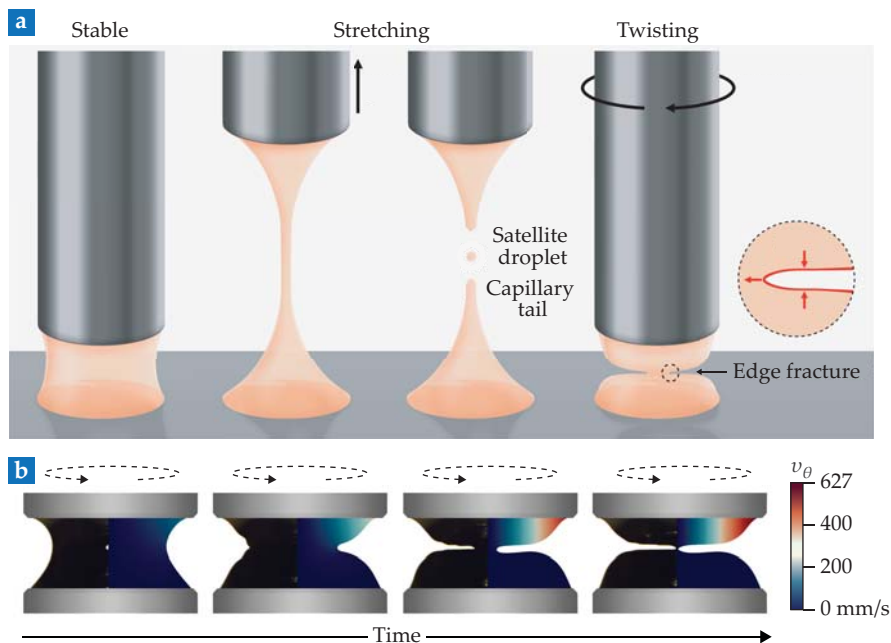


FIGURE 2. VISCOELASTIC FLUIDS between two surfaces. **(a)** Below a critical nozzle height (left), a fluid (pink) forms a stable connection between the target substrate and the nozzle. When the nozzle is above a critical height (center), the fluid breaks and forms undesirable satellite droplets and strands known as capillary tails. If, instead, the nozzle rotates (right), an indentation formed by the normal stresses (red arrows), shown in the inset, cleanly severs the fluid bridge. **(b)** Experimental photos of silicone oil rotated at 35.3 Hz (left half of each image) and simulated azimuthal velocity v_θ (right halves) show how the indentation forms in the side of the bridge and propagates to the center. (Adapted from ref. 1.)

roughly equal radius and height? To verify the connection, the group teamed up with Patrick Anderson and his graduate student Frank van Berlo of Eindhoven University of Technology in the Netherlands to perform calculations complementing the experiment.

In his simulations, van Berlo had to verify that the liquid bridge system possessed properties characteristic of edge fracture. For example, the indentation should have a normal stress tugging its tip toward the center and normal stresses squeezing its upper and lower surfaces, as shown in the inset of figure 2a. Tweaking the right set of inputs to test the relationship between the normal and shear forces and the formation of indentations, van Berlo confirmed edge fracture as the origin of his colleagues' observations. Their study thus expanded the parameter space of such research.

Edge fracture is typically viewed as a problem in rheological measurements because it makes results harder to interpret. But for clean dispensing, edge fracture is advantageous. "Instead of avoiding the elastic property of the viscoelastic

liquid bridge, we amplify it to the extreme where fracture occurs," says Shen.

The simplicity of the researchers' twisting technique means it's feasible in industrial settings. One potential application is food engineering: The rotating nozzle could neatly apply jam to sugar cookies on a conveyor belt, for example.

But some fundamental questions remain. Although researchers now know the mechanism behind the breakup, it isn't clear why the radius decays according to a power law when rotated. Shen and her collaborators plan to partner with a theorist to further explore the issue and to derive an analytical equation for the decay. Such an equation may provide a route to novel methods for measuring rheological properties of viscoelastic fluids, such as shear-induced normal stresses, that have been difficult to probe by traditional methods.

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