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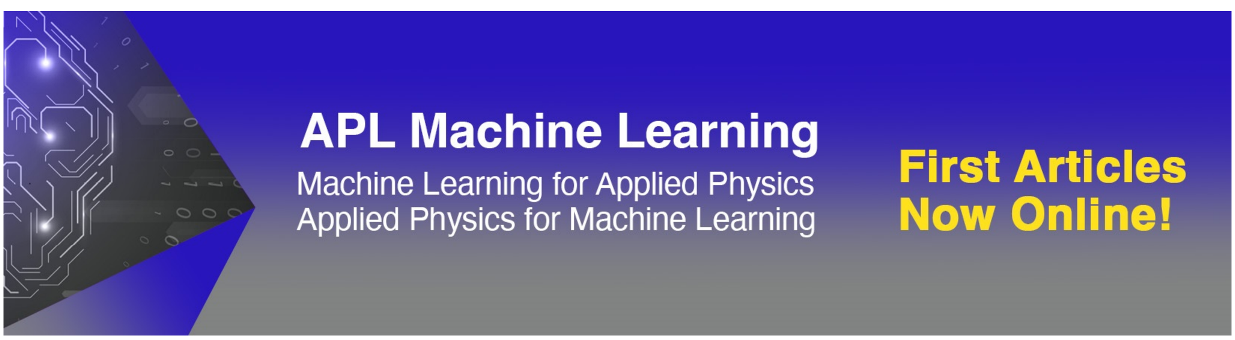

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ABSTRACT

The mechanical experience of consumption (i.e., feel, softness, and texture) of many foods is intrinsic to their enjoyable consumption, one example being the habit of twisting a sandwich cookie to reveal the cream. Scientifically, sandwich cookies present a paradigmatic model of parallel plate rheometry in which a fluid sample, the cream, is held between two parallel plates, the wafers. When the wafers are counter-rotated, the cream deforms, flows, and ultimately fractures, leading to separation of the cookie into two pieces. We introduce *Oreology* (/ɔriːˈɒlədʒi/), from the Nabisco *Oreo* for "cookie" and the Greek *rheo logia* for "flow study," as the study of the flow and fracture of sandwich cookies. Using a laboratory rheometer, we measure failure mechanics of the eponymous Oreo's "creme" and probe the influence of rotation rate, amount of creme, and flavor on the stress–strain curve and postmortem creme distribution. The results typically show adhesive failure, in which nearly all (95%) creme remains on one wafer after failure, and we ascribe this to the production process, as we confirm that the creme-heavy side is uniformly oriented within most of the boxes of Oreos. However, cookies in boxes stored under potentially adverse conditions (higher temperature and humidity) show cohesive failure resulting in the creme dividing between wafer halves after failure. Failure mechanics further classify the creme texture as "mushy." Finally, we introduce and validate the design of an open-source, three-dimensionally printed Oreometer powered by rubber bands and coins for encouraging higher precision home studies to contribute new discoveries to this incipient field of study.

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I. INTRODUCTION

Rheology is broadly defined as the study of the flow of materials with complex or non-Newtonian viscosity. Within kitchen-relevant flows, rheology has been used to address diverse challenges in food science[1] in order to rigorously understand and engineer the deformation and flow of these materials at kitchen, laboratory, and industrial scales. For an accessible introduction to practical rheometry, the reader is referred to Ghanbari *et al.*[2] Rheology applied to food science has found applications ranging from understanding the structure of cheese using fractional calculus models[3] and improving the processing of chocolate to more evenly distribute cocoa butter and thereby enhancing quality[4] to understanding how flow properties[5] and microstructure[6] influence the perceived texture of a wide range of foods. This area of study more recently has expedited the industrial development of new specialty foods, giving a framework to study the composition and flow of gluten-free batter and breads,[7] modeling the texture of starch thickeners for sauces,[8] and informing the choice of sweeteners used in low-calorie chocolate to create optimal yield stress and "sensory acceptance" of the sweets,[9] as the sensory perception of chocolate is heavily influenced by flow and composition.[10]

For materials with multiple ingredients and time-dependent properties, rheological study may be particularly insightful for understanding and tuning the properties. For example, the flow of Swiss cheese fondue may be reliably tuned by adding starch (corn flour) or ethanol (wine),[11] while emulsions like mayonnaise restructure significantly over time after shearing,[12] requiring careful care of their composition and preparation using bulk and interfacial rheology.[13]

While rheology cannot address questions like whether beans belong in chili, or whether a spoon or fork is the more appropriate utensil for mac 'n' cheese, it can describe why larger grains of cereal or larger nuts rise to the top of mixtures when shaken (by granular convection[14]), quantify useful food descriptors like "creamy," "mushy,"

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"slippery," "rubbery," and "astringent,"[5,15] and pinpoint ingredients and length scales that imbue these textures. Fluid mechanics beyond rheology has also been applied to understand and improve food science,[1] including revealing better methods to dip biscuits into morning tea (horizontally, not vertically) by understanding liquid flow through porous carbohydrate media,[16] showing why microwaving tea is less effective than heating a teapot from below (due to fluid convection),[17] clarifying what causes cold milk droplets to bounce across the surface of hot tea or coffee,[18] and solving how you can carry your nearly-full coffee cup without spilling (i.e., by walking backward).[19,20] At the kitchen sink, interfacial fluid mechanics can describe the changing appearance of bubbles as they drain.[21]

Understanding the flow behavior of food ingredients and products has widespread impact on economies of production, public health, and individual diets. Likewise, the experience of consumption (i.e., feel, softness, and texture) of many foods is intrinsic to their enjoyable consumption, with one example being the habit of twisting a sandwich cookie apart before eating. In this study, we seek to address this challenge for our everyday trilayer laminate composite, the Oreo cookie. Although unstudied compared to starches, doughs, and condiments, sandwich cookies present a canonical example of parallel plate rheometry, in which a fluid sample (the "creme") is initially fixed between two parallel plates (the wafers). When the wafers are counter-rotated, creme torsionally deforms in shear, flows, and ultimately fractures, leading to separation of two cookie parts [Figs. 1(a) and 1(b)]. In a cohesive or bulk failure event, the creme itself will flow until it ruptures and will be distributed between the two cookie wafers. In adhesive or interfacial failure, the creme instead delaminates nearly entirely from the wafer–creme interface at one wafer and remains adhered only to the second wafer. In our tests, adhesive failure is most common when manipulating cookies by hand [Figs. 1(c)–1(e)] or laboratory equipment, with some exceptions when some creme appeared to cling to stochastic asperities on the second wafer.

Importantly, the postmortem creme distribution of sandwich cookies is found to be consistently oriented within a box [Figs. 1(c)–1(e)] for all boxes we tested, as has been suggested earlier.[22] During the manufacturing process, Oreos are constructed by dispensing creme onto a first wafer (which we call wafer 1), followed by a second wafer (wafer 2) being placed on top.[23] This difference in initial wafer–creme contact supposedly influences the relative creme–wafer adhesion.[22] Due to the high regularity of manufacturing, this results in the first wafer having a slightly higher level of creme adhesion, and this orientation is preserved when Oreos are placed into the final product box. For instance, in a regular-sized box of regular Oreos obtained in Cambridge, MA, wafer 1 predominantly faces toward the left side when the package text is upright, whereas in a "family size" box of regular Oreos, wafer 1 faces to the right side when the package text is upright, both showing 80% of Oreos retaining creme on the wafer facing that preferred side, rather than 50% as would be expected from random chance. We have observed that this in-box preferred orientation varies between flavors and creme "stuf" or creme filling levels, although it is consistent among multiple boxes of a single variety. This challenge prompts the core of our study to understand the influences of cookie breakage kinematics and inherent cookie properties to control failure stress, failure type, and creme distribution and ultimately to robustly identify whether Oreos are—or can be made to be—"fair," so that they split creme equally between wafers without bias. To what extent is the result predetermined by manufacturing?

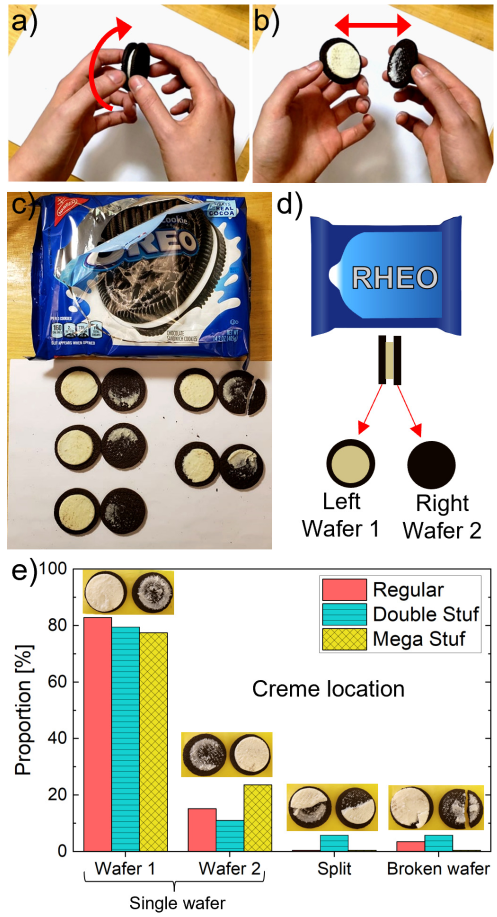

FIG. 1. (a) What happens when you twist an Oreo? (b) Eventually it splits into two parts, exposing the creme. (c) and (d) We observed that in a typical failure profile for Oreos from newly opened boxes, the creme most often tends to remain on one side, "wafer 1," with a consistent orientation per box. In this case, wafer 1 faces to the left side of the upright box for a standard size package of regular Oreos. The creme occasionally splits between sides, often due to defects or small fractures in one or both wafers. (e) This is consistent for cookies with different creme levels, with a strong bias toward wafers facing one side of the box rather than the other, facing left for regular, right for double, and up for mega (where rows are oriented vertically rather than horizontally) in standard size packages.

While Oreos are not commonly considered to be a fluid, Oreo creme is a member of the class of flowable soft solids known as "yield stress fluids," which are fluids that act as soft solids when unperturbed and only flow under a sufficiently large applied stress.[24] Yield stress fluids include a diverse range of important food materials in addition to Oreo creme such as cookie dough, frosting, ice cream, peanut butter, guacamole, and ketchup as well as foams, cosmetics, biological gels, screen-printing and robocasting inks,[25] snow and lava,[26] drilling muds (e.g., bentonite dispersions), concrete and mortar. They also include dry but flowing powder ingredients and granular materials,[27,28] from flour and corn starch to collections of sprinkles, marshmallows, fried rice,[29] and fire ants.[30] (We would be curious as well

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about how the bite-size, edible protein models developed by Baumer *et al.*[31] would roll down an incline.)

Moreover, the measurement of fluid failure behavior into which sandwich cookie separation can be categorized is a broader topic within rheology. In particular, the study of failure of such amorphous ("glassy") colloidal soft matter and, particularly, stress overshoots and related shear-banding that occur during strain-controlled failure are an active area of experimentation and simulation within soft glassy rheology to understand the underlying physics.[32,33] Further, edge fracture is a persistent challenge in parallel plate rheometry wherein normal stress differences build up by application of torsional shearing strain, causing the fluid meniscus to deform and propagate a radial crack near the outer edge,[34,35] as may happen to initiate the failure of Oreo cookies. While this effect is usually fatal to experimental testing of material properties, it has been productively exploited to rapidly pinch off threads of viscoelastic inks in three-dimensional (3D) printing processes,[36] which otherwise leads to stringing defects during printing. In addition, complex failure mechanisms can occur with torsional failure of thin disks, especially after such edge fracture surfaces have formed.[37] And so, while cookies may be nutritionally lacking, they present an enriching abundance of topics for scientific study.

We introduce *Oreology* (/ɔriːˈɒlədʒi/), from the Nabisco® *Oreo*® for "cookie" and the Greek *rheo logia* for "flow study," as the study of the flow and fracture of sandwich cookies. We begin this study with a validation (Fig. 1) of previously reported[22] suggestions for what causes the creme filling to separate predominantly onto one wafer or the other based on initial orientation within the product packaging. In Sec. II, we present equations to understand creme material deformation, torsional shear strain, and the resulting shear stress in counter-rotated parallel-plate mechanical tests. In Sec. III A, we test Oreos using a laboratory rheometer in a protocol also known as torsional gelometry when applied to cheeses.[15] We monitor the shear stress–shear strain response to observe the characteristic failure response and report key mechanical properties of the creme filling. In Sec. III B, we investigate how the stress and creme distributions are affected by deformation rate (which mildly influences the resulting stress, indicating viscoelastic behavior), the amount of creme (which is not influential), and the flavor (which is not influential). In Sec. III C, we map out the spatial dependence of cookie failure orientation in relation to its position within a box. In Sec. III D, we investigate the observation that occasional boxes of cookies will contain cookies that predominantly all exhibit cohesive rather than adhesive failure of the creme. In Sec. III E, we explore time-dependent creep of the creme, which manifests as "delayed yielding,"[38] under which a constant applied stress causes Oreo creme to flow and break, not immediately but only after long times. In Sec. III F, we follow the degradation of chocolate wafer strength over time following milk imbibition, which causes significant structural loss in the first 30 s after contact.

When considering how to enable the broader accessibility of kitchen science, and rheometry overall, we must confront the fact that a laboratory rheometer is not widely accessible. For these reasons, "frugal science" and open-source measurement tools have taken off,[39] creating cost-effective research equipment such as origami microscopes;[40] wound string-powered centrifuges;[41] LEGO-based microfluidic systems,[42] microscopes,[43] and optical setups;[44] and 3D printed tools of many varieties including high-accuracy instrumentation for rheometry[12,45] and microfluidics.[46] And also, in Sec. III G, we present a 3D-printed torsion testing device designed for Oreos and similarly sized round objects. We conclude in Sec. IV with some ideas for future work and areas of study.

II. UNDERSTANDING SHEAR STRESS AND STRAIN IN SANDWICH COOKIE FLOW

In laboratory rheometry, a sample fluid is typically placed between two coaxial parallel disks. The lower disk is held fixed while the upper disk is rotated at a constant rotation rate Ω. This creates a wall-driven laminar (Couette) flow with internal tangential velocity ranging linearly in height from $v = 0$ at the fixed lower disk to $v = r\Omega$ at the upper disk, where r is the radial position from the center of the disk [Figs. 2(a)–2(c)], and z is the height above the stationary lower disk. The velocity field in the fluid is, thus,[47]

$$v_\theta(r, z) = \frac{\Omega r z}{H}. \tag{1}$$

For sandwich cookies, the analogy is apparent: the wafers are the parallel plates, and the creme is the fluid in between. When one wafer is fixed and the other is rotated, the central cylindrical disk of creme deforms until failure. Through analogy to this parallel plate setup, we calculate the material-level descriptors (shear stress, shear rate, and shear strain) for twisting Oreos, based on measured and applied quantities (torque and angular displacement). The shear rate $\dot{\gamma}$ arising from the rotation rate Ω with creme height H will be

$$\dot{\gamma}_{rz} = \frac{\partial v_\theta}{\partial z} = \frac{\Omega r}{H}, \tag{2}$$

which varies from 0 at $r = 0$ to a maximum value denoted by $\dot{\gamma}_R$ at $r = R$, the creme radius:

$$\dot{\gamma}_R = \frac{\Omega R}{H}. \tag{3}$$

The maximum shear strain γ_R arising from the given angular displacement θ will be[47]

$$\gamma_R = \frac{\theta R}{H}. \tag{4}$$

And the shear stress at the outer perimeter ($r = R$) corresponding to torque M is

$$\sigma_R = \frac{2M}{\pi R^3}. \tag{5}$$

For simplicity of notation, we use γ and σ without subscripts to refer to these quantities, as we only consider the value at $r = R$ in the following measurements because we focus on failure, which initiates at the location of maximum stress/strain. In fact, due to this non-homogeneous strain, varying as a function of radius, additional corrections could be applied to recover more accurate measurements for large amplitude deformations.[48] For linear elastic materials at low strain (far below yielding), we expect the shear stress to be linearly related to the shear strain multiplied by the elastic shear modulus, G, or

$$\sigma = G\gamma. \tag{6}$$

In our analysis, the height H used in calculations refers to the height of the cream disk alone, even when a rheometer holds wafers as

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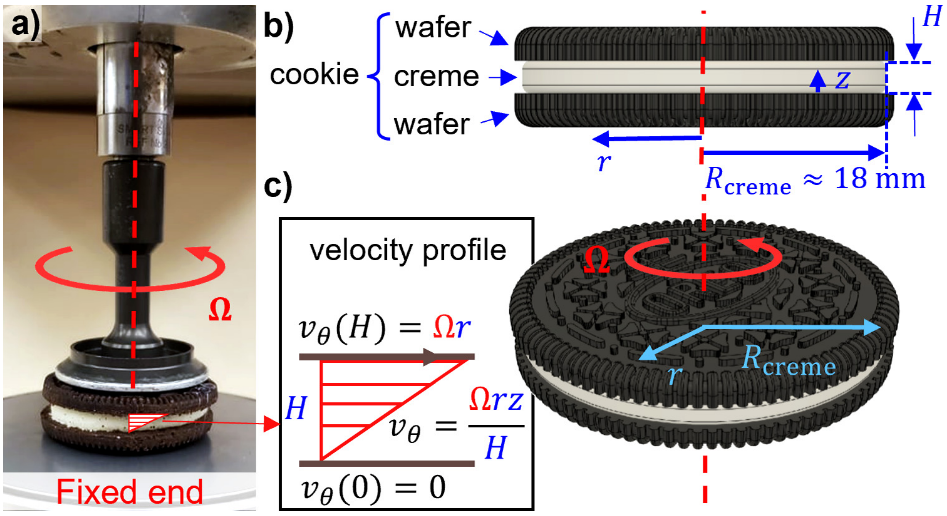

FIG. 2. (a) A cookie is mounted for testing on parallel plate fixtures of a laboratory rheometer and adhered to the metal plates by a low-temperature thermoplastic adhesive. (b) The sandwich cookie is a layered composite with two solid wafers enclosing a central cream layer. When one wafer is rotated relative to the other, the creme deforms in torsion. (c) The resulting velocity field within the creme is a function of applied rotation rate, material height, and radius from the center. In this figure, red colors indicate kinematic properties, and blue colors indicate geometric properties in the colored web version of this article.

well because the wafers are significantly stiffer than the cream. We found the linear elastic shear modulus, G, of the wafers to be at least 280 kPa, while the modulus of cream filling is ≈41 kPa, validating this approximation. The moduli were measured by small amplitude oscillatory shear tests on the rheometer.

III. RESULTS

A. Fracture of creme

When the cookie is rotated on the torsional laboratory rheometer (DHR-3; TA Instruments) at a constant speed (here, $\Omega = 0.1$ rad/s, or about 3.7 rotations per minute), the measured stress shows three mechanical regimes (Fig. 3). Initially, (1) a linear elastic response occurs, indicating a solid-like response of the creme to the applied strain. The stress–strain curve has an initial slope equal to the elastic shear modulus, G. Next, (2) deviation from linearity indicates material plasticity and onset of irrecoverable yielding, and the stress maximum at the failure stress σ_f and failure strain γ_f marks material failure. Finally, (3) structural breakdown of cookie integrity propagates throughout the creme, typically due to creme delamination from wafer 2, which was affixed to the top rheometer plate for all our studies after identifying the native cookie-preferred orientation in each box by manual tests. Results are shown in Fig. 3 for several cookies each taken from two separate boxes purchased on separate days (red and black lines, respectively) with the average response ($n \geq 4$) for each shown in bold for clarity. Annotations indicate the failure stress σ_f, failure strain γ_f, and slope corresponding to the linear elastic modulus $G = \sigma/\gamma$ at low strains, which are also compared in Fig. 4 showing statistically different failure stress and linear elastic modulus, and statistically similar failure strain between cookies from the two boxes. The corresponding torque required to break open the Oreos in pure rotation is about 0.1 N·m. In comparison, the torque required to open a soda bottle cap is around 2 N·m, and a round doorknob may require 0.6 N·m to turn. Per NASA's human capabilities catalog, humans are able to apply twisting forces up to a range of 1 to 5 N·m using thumb and forefinger grip alone, or up to 15 N·m using full hand grip and forearm rotation.[49] By comparison, sandwich cookies are easy to open.

Within the realm of food science, the range of failure strains exhibited by the Oreo creme is on the brittle end, far below the failure

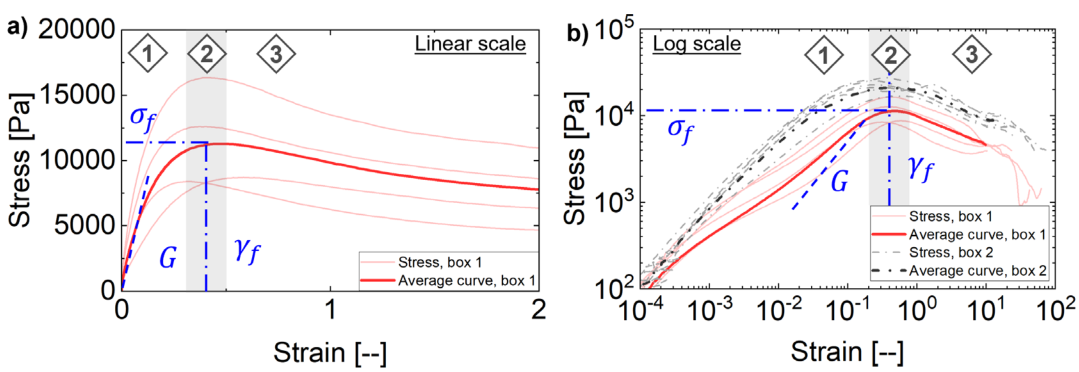

FIG. 3. When the cookie is rotated on the rheometer at a constant speed of 0.1 rad/s, the shear stress is measured and plotted (a) on linear axes and (b) on logarithmic axes. The results show three mechanical regimes: (1) a linear elastic response, (2) a stress maximum indicating material plasticity and yielding, and (3) structural breakdown of cookie integrity, typically due to creme delamination from the top wafer (wafer 2). Results are shown for $n \geq 4$ repeats of cookies from two separate boxes purchased a week in advance (red solid lines in the online version of this article) and the day of the trial (black dash-dotted lines) with the average line for each box shown in bold for clarity. Annotations indicate the failure stress σ_f, failure strain γ_f, and slope corresponding to the linear elastic shear modulus $G = \sigma/\gamma$ at low strains for the mean red curve.

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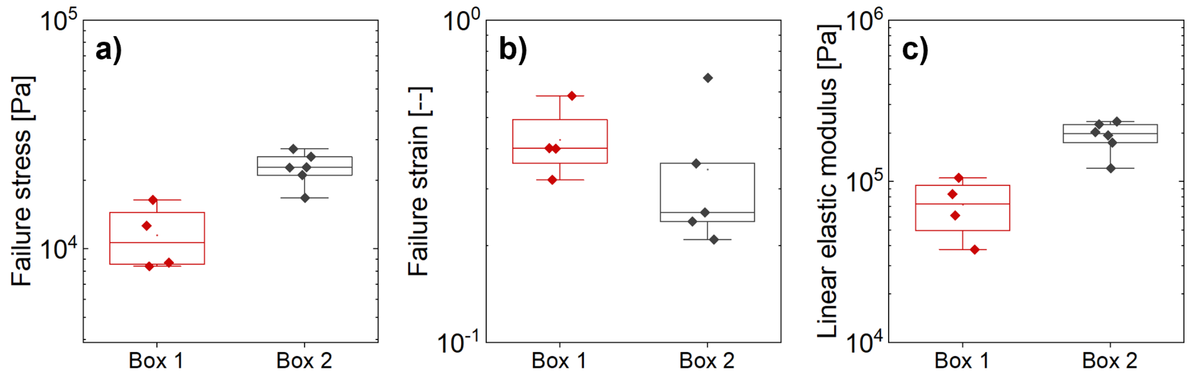

FIG. 4. The material mechanics are extracted to compare values between boxes. We use box plots (naturally) to visualize the comparative distributions of (a) failure stress σ_f, (b) failure strain γ_f, and (c) linear elastic shear modulus $G = \sigma/\gamma$ at low strains. While systematic differences in the measured attributes are visible for all three parameters, only the reported values of failure stress and linear elastic modulus are statistically different ($p < 0.05$) between boxes.

strains of food gum additives and thickeners[50] and roughly equivalent to the failure strains observed in crumbly Romano or Old Amsterdam variety cheeses[15] or foie gras.[6] The failure stress of the Oreo creme is double that of a typical cream cheese[51] or of peanut butter,[52] and of the same magnitude as the failure stress of a soft Havarti or mozzarella cheese, but much less than typical cheeses, and so the creme is relatively soft. The failure stress and strain together place the Oreo creme within what has been previously identified as the "mushy" texture regime (as opposed to brittle, tough, or rubbery).[15]

B. Dependence of fracture on flavor, rotation rate, and creme "stuf" level

Cookie connoisseurs may be prone to slowly or rapidly twisting their sandwich cookies (perhaps based on hunger or anxiety levels). To address the influence of these habits scientifically, in our laboratory rheometer, the upper wafers were rotated at a variety of controlled rates [$\Omega = 0.001$ to 10 rad/s, Figs. 5(a) and 5(b)]. We found that rotation rate influences the failure stress and strain by up to an order of magnitude, so that faster twisting results in higher yield stress and strain. This rate-dependence of the failure stress indicates a viscoelastic response in the creme, because a purely elastic or elasto-plastic failure would have a consistent failure stress at all applied rates. Rotation rate does not, however, influence the creme distribution—except at the highest testable rate, which tended to energetically free the creme from both wafers nearly simultaneously, and, in some cases, to also fracture the wafer [shown in the inset to Fig. 5(b)].

Next, the height of creme filling, or "stuf" level, was found to have only small influences on the failure stress and strain, as shown in Figs. 5(c) and 5(d). It was observed that double stuf cookies were filled to the largest outer radius, and so they required the most torque to separate, with some exceeding the torque limit of the laboratory rheometer ($M_{max} = 200\ \mu\mathrm{N}\cdot\mathrm{m}$) and causing greater uncertainty in these measurements. As has been previously observed, "double" and "more" stuf levels are in fact only about 1.9 and 2.7 times more stufed with creme by mass than the regular variety.[53] Finally, we analyzed the influence of creme and wafer flavors, comparing Golden, Dark Chocolate, and Team USA triple-stuf Olympic varieties, as shown in Fig. 5(e). Again, the required stress did not depend on creme/cookie flavor. Meanwhile, the wafer flavor influenced the likelihood of wafers to break. For instance, the Golden variety wafers fragmented during failure tests, causing creme to redistribute based on the wafer failure planes onto segments of both wafers. Two cookies are shown in Fig. 5(f) post-failure (but pre-consumption).

C. Mapping creme failure in a box

To understand cookie failure types within a full box of Oreos, all cookies were tested while keeping track of original location. In a single, freshly opened box of Family Size regular Oreos, which contains three rows of 16 cookies facing left–right in line with the label text, we found that cookies tend to have broken wafers near the box edges, creme staying on the right-most wafer in cookies on the left side of the box, and creme staying on the left-most wafer in cookies on the righthand side of the box (Fig. 6). Here, the terms "left" and "right" are oriented such that the package text is upright when the box is viewed from the front. The results show some randomness but average out to show consistent overall trends with several interesting features. The original spatial location of the Oreo in the box contributed a statistically significant impact ($p < 0.05$) on the creme distribution post-failure, with cookies on the left-most edge of the box statistically more likely to be fractured than cookies in other locations, cookies on the left-hand half of the box more likely to fracture with creme entirely on the right-most wafer, and cookies on the right-hand half of the box more likely to fracture with creme entirely on the left-most wafer (Fig. 6). Therefore, in addition to the observation that overall creme is most often oriented toward the right for a randomly selected cookie in this type of box, in a competing trend, the creme also falls most often on wafers facing inward into the box and away from the nearest (left or right) edge of the box. This may indicate that environmental impacts (ambient heat or mechanical perturbations) influence the cookies in individual boxes, having the greatest influence on cookies near the perimeter. As these influences are uncontrolled by individual consumers, this sensitivity may diminish the predictability of creme failure type and location between different boxes of cookies. No similar trends were observed comparing top-to-bottom distribution among rows rather than columns. How much this distribution changes between different boxes, cookie types, and season or other environmental impacts, and why, may be a topic for future study.

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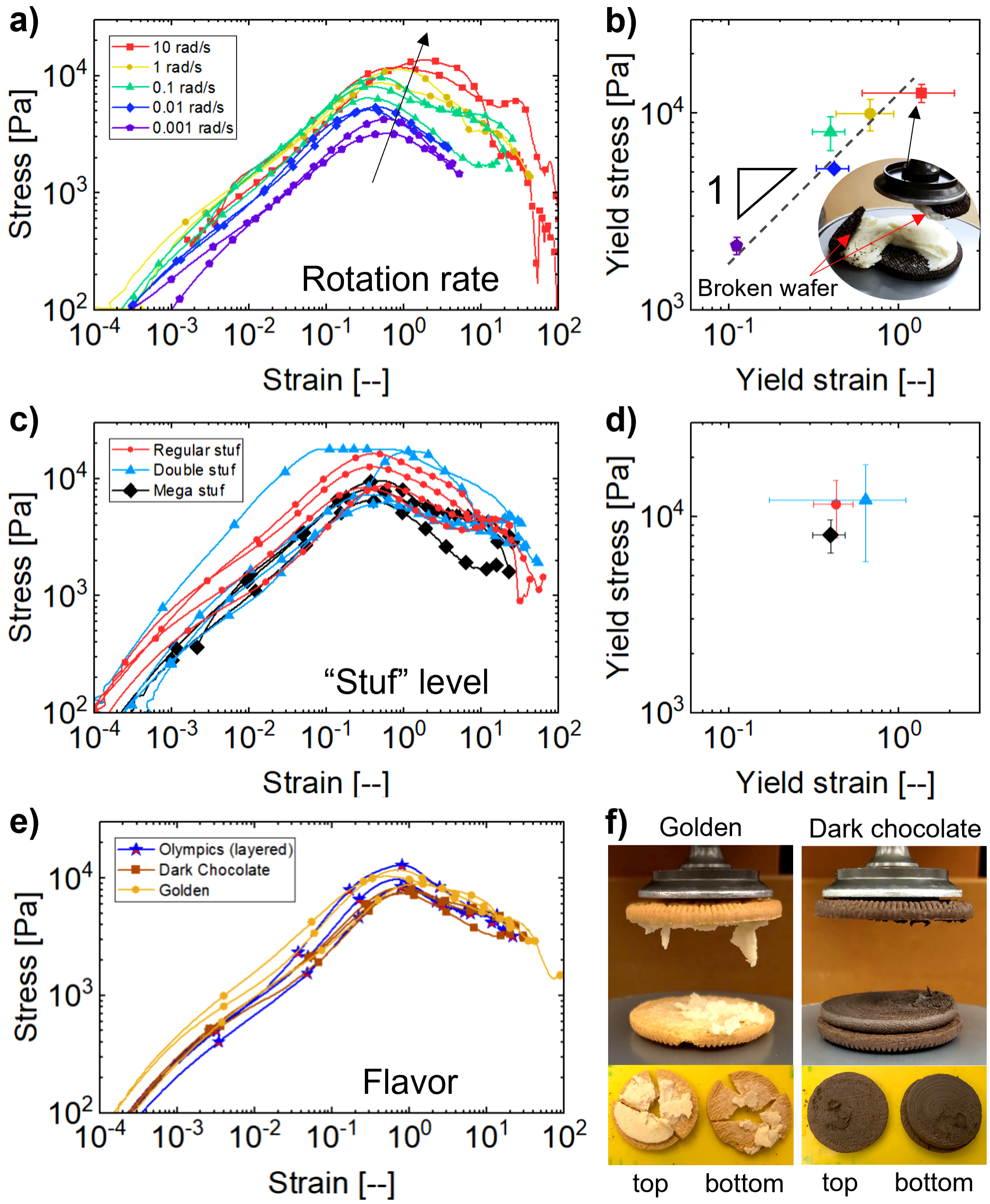

FIG. 5. (a) and (b) Creme failure tests were repeated for different rotation rates, and our tests revealed a rate dependence, with the faster rotation requiring higher stress and strain. At the highest speed only, 10 rad/s (about 370 rotations per minute, as fast as a typical ceiling fan rotates), the wafer tended to break along with the creme, as shown in the inset to (b) of the cookie post-failure but still mounted on the rheometer. The dashed line indicates a line of slope one relating yield stress to yield strain. (c) and (d) The "stuf" level or height of creme was not found to influence mechanics of failure or creme distribution, and (e) the Oreo flavor did not influence stress levels, although (f) flavors seemed to influence how likely a wafer was to break, with images shown for one cookie each after twisting for the Dark Chocolate and Golden flavors. For the Golden variety, this wafer breakage was substantial enough to influence creme distribution onto some top-wafer segments and some bottom-wafer segments. Color to distinguish plotted lines is available in the web version of this article.

D. Creme distribution control and predictability

In almost all cases, we found cookies in newly obtained boxes to exhibit adhesive failure of the creme. However, after long times of being opened, or for the occasional newly opened box, nearly every cookie in the box split differently, leaving substantial creme on both halves. When this tendency toward cohesive failure was found to occur in a given box, cookies in these boxes tended to have creme filled between wafers to a greater radial extent without having greater total

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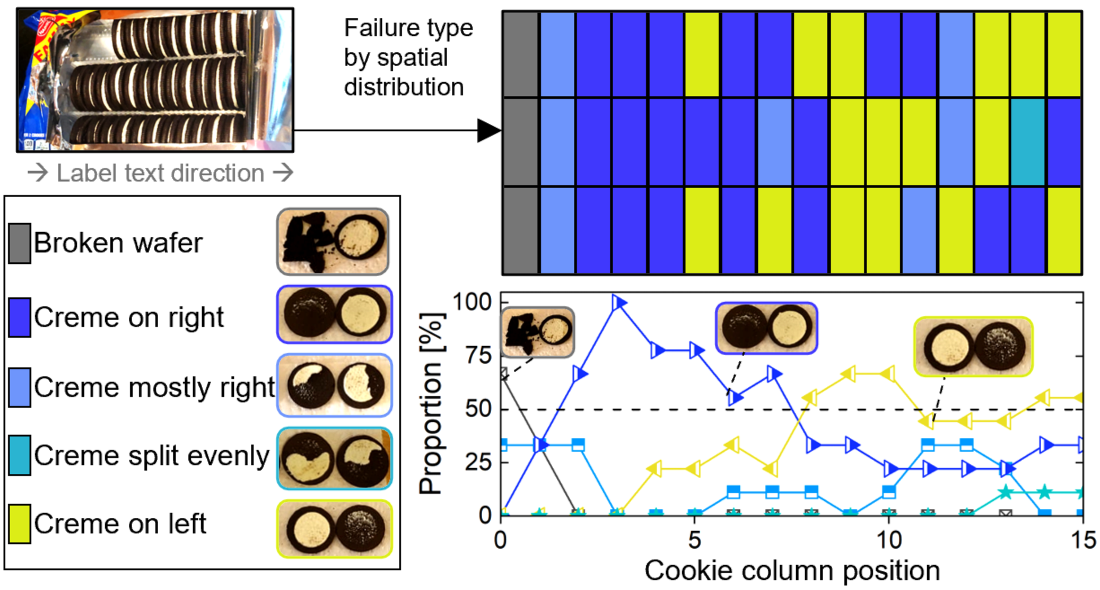

FIG. 6. Creme distribution for all cookies mapped within a single box of Oreo cookies shows directional biases within the box, shown as a color map for a box with label text running to the right, with color available in the web version of this article. Creme overall tends to be on right-facing cookies but also more likely tends to fall to the left wafer for cookies on the rightmost side of the box. Left and right are oriented such that the package text is upright. The Plotted proportions shown in the lower right figure are calculated for cookie positions averaged over the entire row and neighboring two column positions for the single box, with inset images labeling the most-likely failure type based on position, showing the differences between the left and right halves of the box.

volume, as shown in Figs. 7(a) and 7(b). This suggested that creme had been allowed to flow after initial production, which would alter the creme itself and strengthen the creme–wafer bond enough to allow cohesive creme division. We could not pinpoint the specific reason for this difference, and systematic treatments of heat, humidity, staleness, mechanical agitation, compression, and preshearing only inconsistently recreated this effect. This change may have been due to variations in the manufacturing process, storage or shipping conditions with hotter temperatures, wafers growing stale, or other effects.

The stress profile measured for different varieties showed a single stress peak denoted σ_f for adhesive failure [Fig. 7(c)]. Meanwhile, multiple peaks occur for cohesive failure due to the yield surface dynamically propagating with increasing strain. Because the maximum yield strain occurs at $r = R$, inner sections of material at $r < R$ experience this yield strain at later time points when the top wafer is rotated at a constant angular velocity Ω. In the case of cohesive creme separation, the creme failure surface was found to not lie parallel to the wafers but had a distinct "cup and cone" morphology, which would be expected for the failure of a brittle solid material, such as a metal, in torsion. This is because the failure plane for brittle materials is expected to be in the direction of maximum normal stress, which in torsional shear is along a 45° angle from the axis of rotation, thus forming a cone;[54] in contrast, failure for ductile materials would be expected for ductile materials in the direction of maximum shear stress, which in torsion is orthogonal to the axis of rotation. In addition, these cohesively failing Oreos followed the same orientation scheme observed previously; the "cup" side with slightly more creme tended to be on Wafer 1. Creme was distributed by cohesive failure evenly for all rotation rates, yielding 55% to 73% by mass on the more creme-laden wafer, with the creme division unaffected by the rotation rate, although a few cookies in this type of box would still exhibit adhesive creme failure.

While the fracture surfaces of ductile materials failing in torsion can be modulated by the applied torque, fatigue effects, and simultaneous tensile stresses[54–56] (i.e., combined loading, or peeling of an Oreo in addition to simply twisting), this was found to not be tunable for Oreos due to the apparent brittle nature of failure. To confirm this result, using a box of cohesively failing Oreos, we explored the effect of helical twisting profiles for failure. These paired a twist with a vertical push or pull with varying rate combinations of the two steps. No systematic trends were observed on the resulting creme distribution (data not shown). For other brands of cookies with more ductile or "creamier" fillings, it is theoretically possible to tune creme distribution by the kinematic profile of cookie twisting alone. It may also be achievable to tune creme distribution yet with Oreo creme at elevated temperatures when creme flows more easily, or through more careful heating and annealing of creme, which has been shown to influence whether colloidal soft matter will fail via brittle or ductile mechanisms.[32] Although detailed exploration of such tuning is outside the scope of the current study, we performed exploratory experiments with lightly microwaved Oreos to confirm this possibility.

E. Creeping flow causing delayed yielding under constant stress (horeology)

Yield stress fluids typically exhibit time-dependent behavior. This inclusion of time dependence on our Oreos may be considered a venture into a secondary new field, "horeology," defined as the combination of horology (the study of time) with Oreology, defined previously. To assess how the Oreo creme distribution may change over time, we

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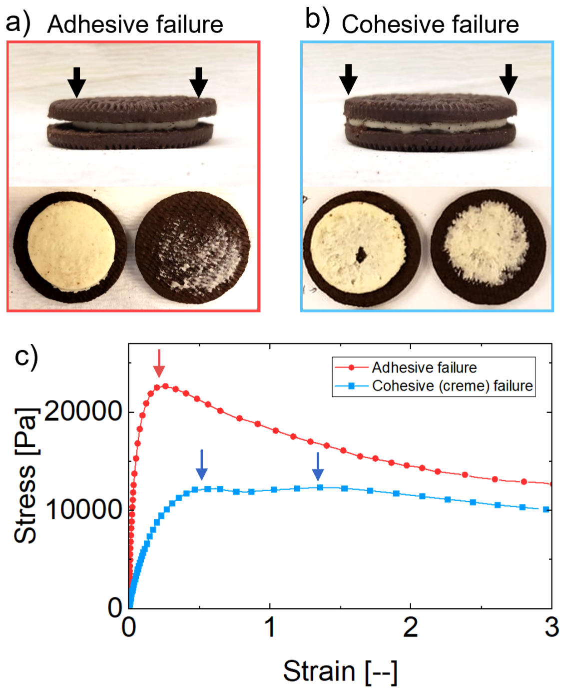

FIG. 7. (a) While most creme layers failed adhesively in boxes of new cookies, (b) cookies exposed to adverse conditions may cause creme to spread from its initial manufactured state, and then cohesive failure was typical for most cookies in the box. These visual signs of changing creme fill levels (indicated by the black arrows in (a) and (b) are typical but not deterministic predictors of failure mode. (c) Failure tests also distinguished between cases in the computed stress–strain curves resulting from the measured torque as a function of imposed rotation angle. There was a single peak stress for adhesive failure, which occurs as a single delamination step, and two or more maxima in stress for cohesively failing creme layers due to the more complex dynamics of cohesive failure propagation along nonplanar surfaces. Cohesive failure was also typically observed to result in a higher failure strain and lower failure stress, as shown here.

performed creep experiments with the laboratory rheometer, holding a constant torsional stress of low, medium, or high values (6.7, 15.5, and 19.1 kPa, respectively) relative to the expected yield stress of ≈17 kPa, with results shown in Fig. 8. The creep compliance, or the quotient of the measured angular strain and applied stress, indicates the amount of material flow in response to the applied stress. When a high stress was applied, cookies yielded immediately shown by a sharply increasing compliance, scaling with time squared (thus being dominated by the acceleration of the upper rheometer fixture, rather than by material behavior). When a low stress was applied, cookies deformed very slightly (i.e., elastically) with some creep behavior emerging at longer times indicated by a change in the power-law slope. At moderate stress, this changing behavior was apparent as a dramatic shift in slope indicating delayed yielding. This phenomenon is also widely seen in creeping solids from mud to mustard[38,57] and has been implicated as a cause of landslides and avalanches due to sudden catastrophic material flow even under constant applied stress. Further, at elevated temperatures, creep is expected to increase, and this phenomenon may partially explain how creme may spread over time as in Fig. 7 while wafers remain intact.

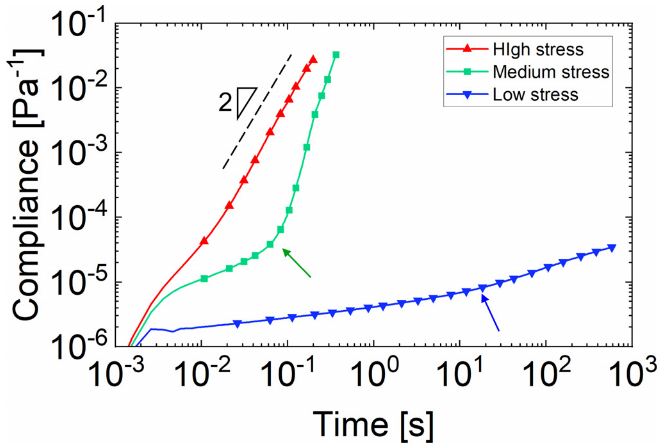

FIG. 8. Creme was observed to yield slowly under applied stress in the laboratory rheometer. Low, medium, and high stresses were applied (6.7, 15.5, and 19.1 kPa, respectively), and the apparent creep compliance (equal to the measured angular strain $\gamma(t)$ divided by the constant applied stress) was monitored. For high stresses, the creme immediately yielded, showing an apparent compliance increasing quadratically with time (i.e., due to the inertial acceleration of the rotating rheometer fixture and attached wafer, with negligible resistance from the ruptured creme filling). For medium and low stresses, the creme showed a delayed response indicative of material creep, eventually flowing under medium stress. Arrows indicate approximate locations of slope change.

F. The influence of milk

Once a cookie has been separated, one is typically left with a wafer with creme and a bare wafer, which both may be dipped in milk to enhance final consumption. A wafer in contact with milk will imbibe through wicking of the liquid into its porous structure, which quickly weakens.[58] The laboratory rheometer can sensitively probe the mechanical properties of such material mixtures as they change over time. We affixed a single wafer to our laboratory rheometer using a thin layer of glue to monitor this process. We measured the modulus of the glue to be three times larger than that of the wafer, and the glue layer was under one tenth of the height in total, and so deformation in the glue layer can thus be safely neglected. Low-fat (1%) milk was added by pouring around the perimeter of the wafer, and the linear elastic shear modulus was monitored using a small amplitude oscillatory shear test at a small strain (≈0.1%). Results show a slight increase in the linear elastic modulus due to swelling, followed by a decrease from an initial value of 560 kPa to a final value of 1 kPa with most change occurring over the first 30 s (Fig. 9). We connected this mechanical decline with manual experiments in which we dipped a single wafer into 1% milk for 5 s to ensure sufficient takeup of liquid[58] and held it by hand suspended from one point on the rim. In this manual test, the wafer was observed to break under its own weight after an average of 30.2 s ($n = 8$), shown by a dashed vertical line in Fig. 9, and corresponding to a loss of mechanics of about 95%. Luckily, in a full cookie, sufficient creme remains to hold cookies intact for longer times (an average of 63 s, $n = 6$, under the same testing protocol), as the (nonporous) creme is not similarly weakened mechanically by the milk. However, the orientation and style of manually dipping a cookie or biscuit into liquid will influence the rate of imbibition and subsequent mechanical collapse, as has been reported

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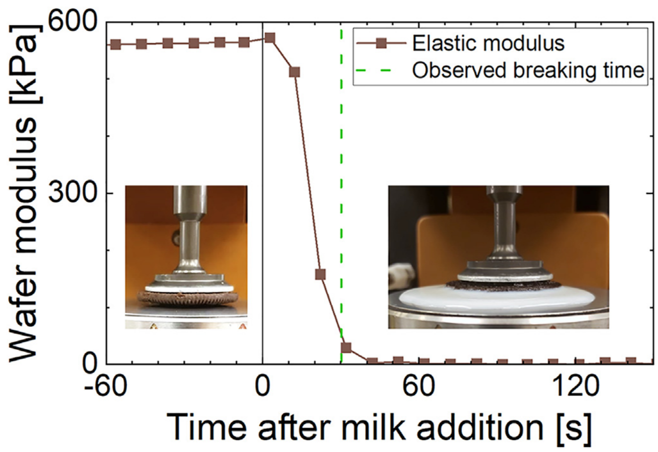

FIG. 9. A wafer was mounted on the laboratory rheometer and subjected to milk imbibition at a time $t = 0$ s. The shear elastic modulus of the wafer dropped to 0.5% of its initial value after 40 s and settled at a new equilibrium static value of 1 kPa. Inset images show the dry wafer on the rheometer at early times and the wafer surrounded by milk at later times.

before.[16] Although this is beyond the scope of the current study, there is likely a "sweet spot" between immersion time to load the cookie with milk and consumption time before loss of integrity. The use of higher-fat milk is also expected to lead to a slower uptake of the liquid due to the milk solids clogging pores in the wafer, as has been shown previously for cereal in milk,[59] which may make this "sweet spot" easier to find. How the macroscale textured ridges on wafers influence fluid imbibition would also be an interesting area of future study.

G. Design of the mechanical Oreometer

Explorations of cookie mechanics varying time, rate, and stress using the laboratory rheometer provide a taste of the potential applications of rheology to quantify and thereby understand flow and fracture of sandwich cookies. To enable further studies beyond the laboratory, we introduce the Oreometer, which is a 3D-printed torsion testing device designed for Oreos and similarly dimensioned round objects (Figs. 10 and 11, Multimedia view). The device requires no power or electronics and has a material cost of $6 (including coins and rubber bands), enabling widespread use.

In the Oreometer, cookies are mounted into two rubber-band powered clamps held on a larger fixture. The rubber band pattern adjusts the holding torque on the wafers, as the clamping force tightens when the band is strained by winding around more posts [Fig. 10(c)]. For brittle cookies with variable sizes, it was important to find the rubber band configuration that held the wafers securely (i.e., to apply enough torque to complete the measurement) without fracturing wafers due to high clamping forces. Next, pennies (quantity N) are loaded into one of the two symmetric "penny castles," applying torque in precise increments [Figs. 10(a4), 10(a5), 10(c4), and 10(c5)]. Staggered castle windows, or *balistraria*, in the penny castles have heights equal to five pennies to expedite counting in

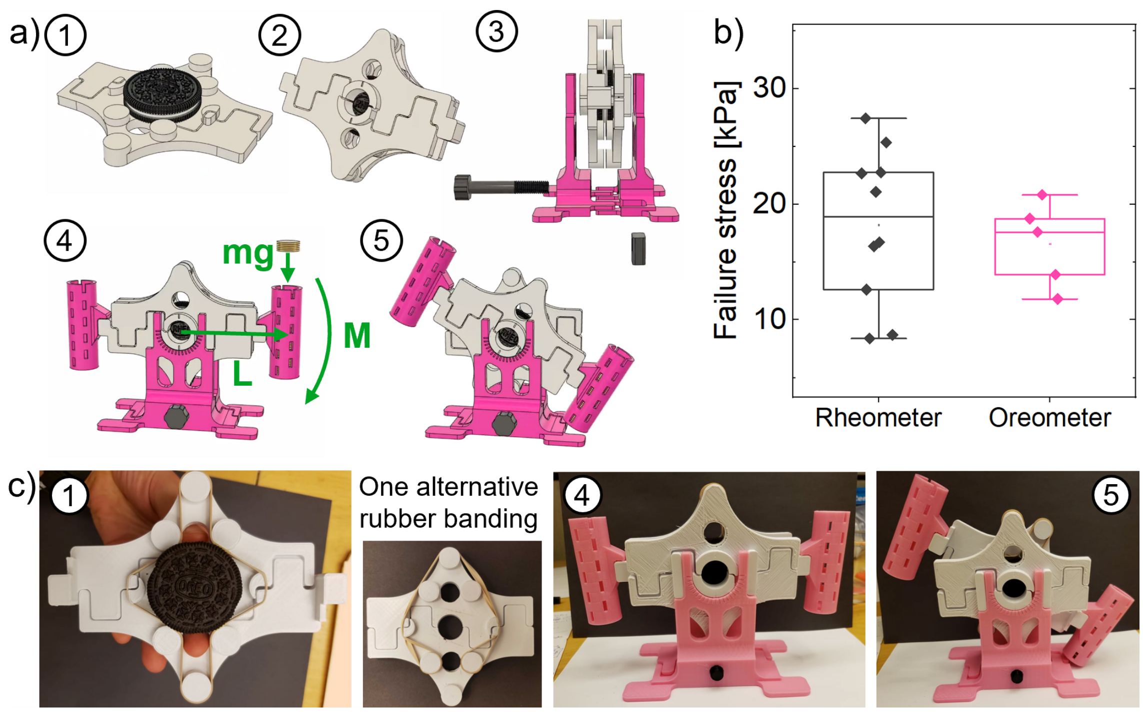

FIG. 10. A 3D printed Oreometer is used to perturb cookies with scientific precision by applying a known and controlled torque. (a) In this device, (1) the cookie is mounted first into one half and then (2) the second half of the rubber band-powered clamps, which are then (3) placed into the vertical assembly mount. (4) "Penny castles" are mounted on the wings, and coins are successively loaded to one side to apply controlled torque until (5) the creme yields. (b) Results replicate values measured by the laboratory rheometer. (c) Photographs demonstrate the same tool, also including the rubber bands in two different arrangements designed to apply different levels of gripping strength in the clamps.

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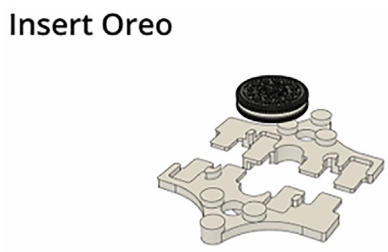

FIG. 11. This computer-rendered animation shows the assembly and use of our Oreometer including inserting the Oreo cookie into the two halves of the clamping fixture, inserting this fixture into the base, and adjusting the base separation, adding "penny castles" to the wings, adding pennies, and finally observing the fractured Oreo. Multimedia view: https://doi.org/10.1063/5.0085362.1

groups of five. The friction torque in the Oreometer opposing twist of the cookie is overcome by less than one penny's weight, $m_{coin}g$. Torque comes from the applied force F along the lever arm between the penny castles and center of rotation, $L = 90$ mm, and the angle θ between the lever arm and the force of gravity. The applied torque M is then

$$M = FL \sin\theta = N m_{coin} g L \sin\theta. \quad (7)$$

Assuming the Oreometer is standing upright without twisting so that $\theta \approx 90°$ as in Fig. 10(a4), the applied torsional stress to the cookie inside is then

$$\sigma = \frac{2 N m_{coin} g L}{\pi R^3}. \quad (8)$$

The stress calculation does not depend on creme height (which influences only the material strain field, not the stress). A video illustration of this device is included in Fig. 11 (Multimedia view) along with the supplementary material containing design files in .stl and .step formats, and a step-by-step tutorial to use the Oreometer for further investigations.

Cookies from both boxes used in Fig. 3 were tested to failure using the Oreometer, and data were compared to those from the laboratory rheometer. We found that the failure stress measured by the Oreometer is not statistically significantly different ($p > 0.05$) from the set of rheometer data [Fig. 10(b)]. Creme distribution results from cookies that were tested to failure on the two devices were also comparable. It was further observed that cookies left in the Oreometer unyielded but with some torque applied may spontaneously yield after some time without additional coins being added. This is due to the same delayed yielding effect reported in Fig. 8.

IV. MOREOLOGY: CONCLUSIONS AND FUTURE WORK

Through a series of experiments with a laboratory rheometer used to hold whole Oreo cookies, we determined that creme distribution upon cookie separation by torsional rotation is not a function of rate of rotation, creme "stuf" (i.e., filling height H) level, or flavor, but was mostly determined by the preexisting level of adhesion between the cookie creme and each wafer. In most cases, creme delaminated from the wafer with a preferential orientation with respect to the package within any one box, allowing prediction of failure direction with 80% accuracy. Despite the consistent failure mode, there was some amount of cookie-to-cookie and box-to-box variation in failure stress and strain. Apparent reflow of creme due to unknown causes had the most significant effect in altering failure type, allowing for improved creme–wafer bonds and subsequent cohesive failure of the creme, splitting nearly evenly between the two wafers. Failure mechanics further allowed us to classify the creme texture as "mushy."

Moreover, questions remain to be explored if we are to fully understand cookie flow phenomena, and for this purpose, we have introduced a home-use Oreometer. A topic of particular interest may be what influences the change from adhesive to cohesive failure. If this is due to altering of the creme structure, then one may wish to explore whether it can be affected by compressing cookies before twisting, humidity, temperature, addition of a flow agent, or fracturing wafers before twisting. Other tests could be done with temperature control by using the Oreometer on cookies quickly withdrawn from the fridge, microwaved slightly, or dipped immediately beforehand in milk, where the device can be placed close to the kitchen appliances to minimize transfer time. The mode of failure of cookies may also be investigated manually by peel tests applied at the same time as torsion to study mixed-mode failure. If cookie manufacturers would like to influence creme distribution themselves, providing wafers with through-holes or texture on inner surfaces should promote creme–wafer adhesion onto both halves. Future studies may examine other sandwich-variety cookies, such as other brands of sandwich cookie, custard creams, macarons, and ice cream sandwiches—wherein temperature would be expected to have greater influence—as well as Nutter Butters, peanut butter between crackers, and other savory snacks. Planar shear tests, rather than torsional shear, may probe whether the fruit paste inside Newtons (previously known as Fig Newtons) indeed have the implied Newtonian flow behavior, or whether they are not only sometimes non-fig-containing, but are also rheologically non-Newtonian [and hence may become known as non-Newton(ian)s]. Our results and methods of investigation may also have widespread application in understanding other torsional events in the kitchen, from braided breads and mixing dough to ideal opening kinematics of stubborn jam jar lids. Finally, the development of an Oreology subdivision within the Society of Rheology might be expected as this field of study evolves and expands.

V. MATERIALS AND METHODS

A. Rheological measurements

Rheological behavior was measured using a stress-controlled shear rheometer (DHR-3, TA Instruments) using a parallel plate fixture (40 mm diameter; TA Instruments) at a controlled temperature of 25 °C. The cookies and creme were initialized with a 0.5 N compressive load after loading in the rheometer to ensure a consistent start point, at which point the vertical gap was fixed and the experiment was performed allowing the normal force to vary. Oreos® (Nabisco) were obtained from the local grocery store, and the wafers were firmly adhered to the plates using thermoplastic adhesive from an "ultra-low temperature" hot glue gun (AdTech, #05690, temperature <100 °C). This glue was measured by small amplitude oscillatory shear to have an elastic shear modulus of 1.4 MPa. Cookies with broken wafers were typically not used. Reported modulus, yield stress, and yield strain were extracted from the stress–strain curves, and statistics were performed on these values using an unpaired two-tailed t-test. P-values of less than 0.05 were considered significant.

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B. 3D printed Oreometer

Designs were made in Autodesk Fusion 360 and printed out of PLA using a Creality Ender 3. Parts were sliced with Cura using a 0.3 mm layer height, 20% infill, 210 °C extruder temperature, and 55 °C bed temperature, and printed with supports for the base halves, Oreo clamps, and penny castles.

SUPPLEMENTARY MATERIAL

See the supplementary material for 3D printing design files and a user-friendly tutorial on getting started with the Oreometer.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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