Localized Transient Jamming in Discontinuous Shear Thickening

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We report direct measurements of spatially resolved surface stresses over the entire surface of a dense suspension during discontinuous shear thickening (DST) using Boundary Stress Microscopy (BSM) in a parallel-plate rheometer. We find that large fluctuations in the bulk rheological response at the onset of DST are the result of localized transitions to a state with very high stress, consistent with a fully jammed solid that makes direct contact with the shearing boundaries. That jammed solid like phase (SLP) is rapidly fractured, producing two separate SLPs that propagate in opposite directions. By comparing the speed of propagation of the SLPs with the motion of the confining plates, we deduce that one remains in contact with the bottom boundary, and another remains in contact with the top. These regions grow, bifurcate, and eventually interact and decay in a complex manner that depends on the measurement conditions (constant shear rate vs constant stress). In constant applied stress mode, BSM directly reveals dramatic stress fluctuations that are completely missed in standard bulk rheology.

INTRODUCTION

An increase in viscosity, \( \eta \), above a material dependent critical shear stress is commonly observed in dense colloidal and granular suspensions [1–7]. This increase can be abrupt if the volume fraction \( (\phi = V_{\text{particle}}/V_{\text{total}}) \) approaches the jamming fraction, \( \phi_j \), and is known as discontinuous shear thickening (DST), while at lower concentrations the increase is gradual and termed continuous shear thickening (CST) [1–17].

CST can arise from the formation of particle clusters due to hydrodynamic forces [9, 15, 20]. However recent work has shown that solid contact and friction, together with the existence of a short-range repulsive force between particles, are likely to play a major role in shear thickening [12, 17, 21, 22]. Wyart and Cates (WC) introduced a phenomenological model in which the shear thickening arises from a transition from primarily hydrodynamic interactions when the applied stress is substantially below a critical stress, \( \sigma \ll \sigma^* \), to primarily frictional interactions when \( \sigma \gg \sigma^* \) [12]. A variety of results from experiments and simulations provide support for the WC model [7, 14, 15, 28, 24], although many questions remain.

One of those questions concerns spatiotemporal dynamics in the shear thickening regime. Temporal fluctuations in bulk viscosity have been observed in macroscopic rheology in DST, and visual observations suggest some associated spatial heterogeneities [2, 7]. Similarly, numerical simulations have revealed stress fluctuations at the particle level and at larger scales [13, 25]. A recent study using ultrasound imaging to measure velocity profiles in sheared cornstarch suspensions in the DST regime revealed bands of varying shear rate and wall slip that propagate along the vorticity direction and proliferate as the stress is increased [26].

Using a novel technique that we have termed boundary stress microscopy (BSM, [27]), we have recently shown that complex spatiotemporal dynamics between high and low stress phases are actually present in the CST regime [16, 28]. BSM revealed the existence of clearly defined dynamic localized regions of substantially increased stress that appear intermittently at stresses above the critical stress. We interpreted those regions as high-viscosity fluid phases, consistent with the high viscosity (frictional) fluid branch predicted by the WC model. In the present work, we extend the application of BSM to a suspension of higher concentration, where the bulk rheological response is in the DST regime, and use a custom rheometer tool that enables us to perform BSM on the entire sample surface. We show that large fluctuations in the bulk viscosity at the onset of DST are the result of localized transitions to a state with very high stress, consistent with the existence of localized regions of a fully jammed solid that make direct frictional contact with the shearing boundaries. That region rapidly bifurcates, producing two separate jammed regions, one that remains in contact with the bottom boundary, and another that remains in contact with the top boundary. These regions grow, bifurcate further, and eventually interact and decay in a manner that suggests a complex coupling between heterogeneous stresses, non affine flow, and density fluctuations.

MATERIALS AND METHODS

Elastic films of thickness of 53 ± 3 \( \mu \)m were deposited by spin coating PDMS (Sylgard 184; Dow Corning) and a curing agent on 40 mm diameter glass cover slides (Fisher
from the angular velocity ($\omega$) according to the rheometer were calculated using the measured torque $R$ based on the torque applied to the tool, we calculate the stress reported by the rheometer (which is calculated based on the torque applied to the tool). Rheological measurements were performed on a stress-controlled rheometer (Anton Paar MCR 301) mounted on an inverted confocal (Leica SP5) microscope using a home made parallel plate tool of diameter 5.2 mm diameter. The gap between rheometer plates was fixed at 0.2 mm. A 1.6X objective was used for imaging and produced a 5.6 X 5.6 mm$^2$ field of view. Deformation fields were determined with particle image velocimetry (PIV) in ImageJ. The surface stresses at the interface are calculated using an extended traction force technique and codes given in ref. [31], which produces a spatial map of the stress in the plane of the surface, $\vec{\sigma}(\vec{r})$. Measurement noise arises primarily from the resolution of the PIV technique. The stress maps reported in Figs. 3, 4 and 7 and shown in the supplementary movies are the stress magnitude, $|\vec{\sigma}(\vec{r})|$. In order to compare with the stress reported by the rheometer (which is calculated based on the torque applied to the tool), we calculate the average boundary stress as $\langle \sigma_{BSM} \rangle = \int_0^R \sigma_\theta(\vec{r}) r dA$, where $R$ is the radius of the tool. Stresses inferred from the rheometer were calculated using the measured torque ($M$) according to $\sigma = \frac{2M}{h^2 R}$. The shear rate was calculated from the angular velocity ($\omega$) of the tool as $\dot{\gamma} = \frac{R}{h} \omega$, where $h$ is the gap between the plates.

RESULTS

As described in the introduction, dense suspensions can show dramatic shear thickening above a critical shear stress. Figure 1 shows the flow curve for the suspension studied here ($\phi = 0.56$). The average viscosity, $\eta$, as a function of the stepwise increasing applied shear stress $\sigma$, measured with the custom small (5.2 mm diameter) parallel plate rheometer tool, indicates that at this volume fraction the suspension is in the discontinuous shear thickening (DST) regime.

Constant Applied Shear Rate

In the constant shear rate measurement mode, the rheometer controls the applied torque (and therefore average shear stress) in order to maintain a constant rotation rate (and therefore constant local shear rate, albeit one that varies with radius in the parallel plate geometry). At relatively small edge shear rates, $\dot{\gamma} \leq 26$ s$^{-1}$, we observe very small temporal oscillations around an average $\sigma$, possibly due to imperfections in the tool (data not shown). When a critical shear rate of $\dot{\gamma}_c \approx 26.5$ s$^{-1}$ is reached, the rheometer (average) $\sigma$ reveals large intermittent fluctuations that are clearly higher than the background of 30 Pa (Fig. 2A, red curves). As $\dot{\gamma}$ is increased further, the spikes in $\sigma$ become more frequent (Fig. 2B,C). Similar behavior is observed with the same measurement geometry but without the elastic PDMS layer (Supplementary Fig. 1), suggesting that the fluctuations do not arise from the compliance of the elastic layer.

In addition to the average stress $\sigma$ reported by the rheometer, we can measure the average boundary stress, $\langle \sigma_{BSM} \rangle$, calculated directly from the deformation on the elastic substrate. Below $\dot{\gamma}_c$, $\langle \sigma_{BSM} \rangle$ remains approximately constant, and barely above the measurement noise (data not shown). Above $\dot{\gamma}_c$, the temporal behavior of $\langle \sigma_{BSM} \rangle$ closely tracks $\sigma$, as shown by the black curves in Fig. 2. The rapid fluctuations in stress are accurately captured by BSM, with excellent temporal resolution. The uncertainty in $\langle \sigma_{BSM} \rangle$ arises primarily from the ~10-20% uncertainty in the PDMS thickness and modulus (see methods). The calculated boundary stresses are...
FIG. 2: Temporal evolution of stress ($\sigma$, red) and average boundary stress ($\sigma_{BSM}$, black) using boundary stress measurements (BSM) for different applied shear rate A,D) 27.3 s$^{-1}$, B,E) 32.5 s$^{-1}$ and C,F) 39 s$^{-1}$ for $\phi = 0.56$.

The real power of BSM is its ability to reveal the spatio-temporal dynamics of stress heterogeneities that cannot be resolved with conventional rheology. For example, the high stress event captured in Fig. 2D is a spatial average of the BSM data seen in Fig. 2B and in supplementary movie 1. Figure 2A shows the average stress vs. time (black) along with the normal force $F_N$ reported by the rheometer divided by the area of the plate, $A_p$ (blue). The measurement of $F_N$ is noisy, but shows large positive values that rise and fall with the shear stress, indicating that the high stress events are associated with strong dilatancy. Figure 2B shows a snapshot of the stress map 0.42 seconds after the beginning of the event (point iii...
in Fig. 3A), showing two localized regions of high stress. In Fig. 3C, we show the time evolution of the stress by “unwrapping” the circular domain onto a rectilinear \( r - \theta \) plane. The high stress region initially appears closer to the edge of the plate, where shear rate is maximum (Fig. 3C, i). As the stress rapidly increases, the high stress region spreads in two, with one region moving in flow direction and another in the opposite direction (iii). The regions grow and periodically bifurcate, leaving behind band-like structures extended in vorticity direction (iii), with stresses below that of the main ‘parent’ region, but still significantly higher than the background stress. The high stress region which moves backwards carries higher stress than one moving forward. When the forward and backward moving regions collide (between iii and iv), the stress rapidly decreases, but the weaker band-like structures persist for some time (Fig. 3: iv-vi, note change in colormap). By comparing the movement of the high stress regions with the top plate we see that the region moving in the flow direction is actually rotating slightly faster than the top plate, while the weaker band-like structures that originated from the region moving in the flow direction rotate with approximately the same velocity as the top plate. The bands originating from the backwards-moving regions remain approximately motionless. Interestingly, after the collision of the parent blobs, the motionless bands disappear, leaving only bands moving with the top plate. This behavior is most clearly seen in supplementary movie 1. The movie is cropped to include only the time surrounding the two high stress events visible in Fig. 2A, and the solid line represents the motion of the top plate (at this shear rate, one full rotation of the top plate takes approximately 3 seconds).

This same temporal evolution is observed in both high stress events occurring at \( \dot{\gamma} = 27.3 \) s\(^{-1}\) (see supplementary movie 1). At \( \dot{\gamma} = 29.25 \) s\(^{-1}\), we observe multiple events whose initial dynamics is identical to those at \( \dot{\gamma} = 27.3 \) s\(^{-1}\) (Fig. 1 supplementary movie 2). A single localized region of high stress that quickly splits into two, one moving in the flow direction slightly faster than the rotating top plate with the other moving opposite the flow direction, with a sharp reduction in stress at the point when the counter-propagating regions collide, and remnant band-like structures that initially rotate with either the top plate or are approximately motionless (Fig. 1: i-xi, circled, and supplementary movies). In contrast to the behavior at smaller \( \dot{\gamma} \), the localized regions of high stress sometimes move in the vorticity direction, and occasionally show more complex dynamics (supplementary movie 2, esp. the last few events).

At still higher shear rates, multiple high stress events overlap, and the rapidly fluctuating average stress (e.g. Fig. 2C,F) is reflective of nearly continual, complex spatiotemporal fluctuations in the boundary stress, with a mixture of high stress regions that propagate in the flow direction, opposite the flow direction, and in the vorticity direction (supplemental movie 3).

**Constant Applied Stress**

In this measurement mode, the rheometer applies a constant torque to the tool, and therefore reports a constant average stress. For a liquid with linear rheology initially at rest, the application of a fixed torque will result in an exponential approach to the steady state shear rate, \( \dot{\gamma} = \sigma/\eta \), with a time constant that depends on the inertia of the tool and the fluid viscosity, as well as geometric factors. This is indeed what we observe for low applied stress (data not shown). However, once the stress is large enough to generate shear rates above \( \dot{\gamma}_c \), the minimum shear rate at which high stress events are observed in the constant shear rate measurements, the increasing shear rate is interrupted by an abrupt drop in shear rate to a value well below \( \dot{\gamma}_c \). The drop is then followed by a resumption of the slow increase in \( \dot{\gamma} \) (Fig. 3A,D, red points, \( \sigma = 126 \) Pa applied stress). At higher applied stress, the rotation rate increases more rapidly, while the abrupt drops occur at slightly higher shear rates, and the time between drops decreases (Fig. 3E, \( \sigma = 180 \) Pa). At still higher stress, the behavior becomes less regular, but the basic features persist (Fig. 3F, \( \sigma = 324 \) Pa). This pattern of behavior is consistent with prior observations of suspensions in the DST regime \([32]\).

As with the measurements at steady shear rate, we can compare the (constant) stress reported by the rheometer with the average boundary stress, \( \langle \sigma_{BSM} \rangle \), calculated directly from the deformation of the elastic substrate. During the period of slow acceleration, \( \langle \sigma_{BSM} \rangle \) is essentially below our measurement resolution, but during the abrupt drops in shear rate we observe dramatic jumps in boundary stress (Fig 5 black points), similar to those observed in both \( \sigma \) and \( \langle \sigma_{BSM} \rangle \) for the constant shear rate measurement (Fig. 2). Note that \( \sigma \) reported by the rheometer is constant in this measurement mode. This highlights the fact that \( \sigma \), calculated from the torque applied to the tool, is not the average stress at the boundary of the suspension when the rotation rate varies, because of the inertia of the tool. Thus the dramatic stress fluctuations revealed by BSM are missed in standard bulk rheology, although they can be inferred from the changes in shear rate with quantitative modeling that incorporates the inertia of the rheometer tool \([32,34]\).

Figure 4 shows \( \sigma_{BSM} \) (black circles) for a single event, along with \( \dot{\gamma} \) (red triangles) and the normal force \( F_N \), blue squares), at an applied stress of \( \sigma = 180 \) Pa. The abrupt change in \( \sigma_{BSM} \) is also present in \( F_N \), as with the events at constant shear rate, and consistent with previous reports \([8]\). Note that the sign of \( F_N \) depends on the relative contribution of lubrication and frictional forces which can result in a negative \( F_N \) even in discontinu-
FIG. 3: Spatiotemporal dynamics of an individual high stress event. A) Rheometer stress and normal force divided by the plate area for the event shown in Fig. 2D ($\dot{\gamma} = 27.3$ s$^{-1}$, rotation period T = 3 s). B) Snapshot of boundary stress map at the peak stress (point iii in A). The rheometer plate boundary is demarcated by the white outer circle. C) Stress map at different time points unwrapped into rectilinear $r - \theta$ coordinates, where $\theta$ is measured from the horizontal (solid line in B) in the flow (clockwise) direction. The event initiates at $t_i = 247.52$ (point i in A) with a localized region of high stress slightly above the horizontal (negative $\theta$), near the outer edge (large $r$). The time elapsed from initiation, $\delta t = t - t_i$, is shown on each panel. The high stress region splits into two, one moving in the flow direction (increasing $\theta$) and the other in the opposite direction. Note that the stress scale is reduced for (iv - vi), after the collision of the counter-propagating high stress regions.

uous shear thickening [35,37]. The events typically have a very sharp onset, allowing us to define an onset shear rate for each event. Figure 6B shows the average of the onset shear rates found for each applied shear stress. For $\sigma = 126$ Pa, only one event is observed; for all higher values of $\sigma$, the error bars represent the standard deviation of the onset shear rates. At the lower $\sigma$, the events are well separated (Fig. 5A,B), while at higher stresses the events begin to overlap, which may explain the change in behavior above 210 Pa.

The typical spatiotemporal dynamics of one of these events is displayed in Fig. 7 (see also supplementary movie 4). The initial evolution is similar to the first phases of the events seen at constant shear rate (Fig. 3): (i) a rapid initiation of a large localized stress close to the edge of the tool where the shear rate is largest, associated with a rapid, large increase in normal stress, followed closely by (ii) a bifurcation into two regions, one moving in flow direction and another in the opposite direction. However, unlike the measurements at constant shear rate, the high stress regions quickly decay, presumably as a result of the sudden drop in shear rate to a value $\dot{\gamma} < \dot{\gamma}_c$, so do not survive long enough to collide after collectively completing a trip around the circle.

**DISCUSSION**

Model for Dynamics of High Stress Phases:

The striking behavior revealed by boundary stress microscopy suggests four distinct stages for the high stress events observed at constant applied shear rates slightly above $\dot{\gamma}_c$: (i) rapid initiation of a large localized stress, associated with a rapid, large increase in normal stress, followed closely by (ii) a bifurcation into two high stress regions, one of which is anchored to the bottom plate, moving slowly upstream, the other of which is anchored...
FIG. 4: Spatiotemporal dynamics of a high stress event at $\dot{\gamma} = 29.25$ s$^{-1}$ shown in the $r - \theta$ plane, as in Fig. 3. The white ellipses highlight non-propagating regions. Note that the stress scale is reduced for (v - xvi).

to the top plate, moving slowly downstream relative to the top plate. (iii) During the migration, the two regions (mostly the one anchored to the top plate) leave behind band-like regions of high stress extended in the vorticity direction and (iv) a dramatic drop in stress when the counter-propagating regions collide.

Phase (i) is consistent with the formation of a localized shear jammed region, or solid-like phase (SLP) that, because of the dilatant pressure resulting from frictional contacts, makes strong physical contact with the boundaries, penetrating the thin fluid layer that normally exists between the suspended particles and the boundaries. This is represented schematically in Fig. 8 where the relatively homogeneous, smoothly sheared suspension (Fig. 8A) is interrupted by a region with a fluctuation to a higher density, where an increase in local shear stress produces an increase in frictional contacts, thereby creating a gap-spanning region of increased frictional contacts (Fig. 8B, blue particles). Alternatively, the initial high stress region might consist of SLPs on the top and bottom plate, with a flowing fluid phase in between. In either case the increased dilatant pressure will create direct contact between the particles and the rheometer tool, and high stress detected by BSM (show schematically by the green region on the bottom boundary). The rheometer stress will increase to the whatever value is necessary to keep the tool rotating, so the bifurcation into two SLPs (phase ii) arises from a fracture of the jammed solid, with one SLP staying approximately anchored to the bottom plate, and the other anchored to the top plate (Fig. 8C).

Because the shear rate in the SLPs is zero (or close to it), the shear rate in the suspension traversing between the SLPs and the rheometer plates will be higher than the average shear rate. We hypothesize that this increased shear rate will drive a transition to a high viscosity (frictional) fluid branch (Fig. 8C, gold particles). The co-existence of two flowing phases of very different viscosities is consistent with our prior BSM measurements of suspensions in CST [16]. The presence of a high viscosity phase helps explain the very large stresses observed in BSM (nearly two orders of magnitude higher than the background boundary stress).

As the top plate rotates, the SLP anchored to the bottom plate (black spheres) moves slowly backwards, perhaps as a result of a densification of the upstream side caused by an accumulation of particles from the flowing suspension. The reverse will happen with the SLP anchored to the top plate (blue spheres), as it is swept through the suspension at a velocity that exceeds the local affine flow speed. This is shown schematically by the additional particles added to the jammed region (Fig. 8D). Because the flowing suspension transitions to the high viscosity fluid phase as it transits the reduced gap between the SLP and the bottom boundary, the SLPs attached to the top plate continue to show up as large boundary stresses on the bottom plate. It is unclear why the growing SLPs would divide and leave behind band-like jammed regions, or what sets the characteristic spacing between the bands, but the bands themselves remain approximately motionless relative to the plates (smaller black and blue regions). When the two large ‘parent’ SLPs collide (iv, Fig. 8F), the interaction presumably
disrupts the network of frictional contacts, resulting in a return to a mostly freely flowing low viscosity suspension, except for the residual band-like structures that are moving with the top plate (Fig. 8G).

A similar picture applies to the events observed at constant applied stress (Fig. 7), except that the nucleation of the gap-spanning SLP is followed quickly by a drop in shear rate. We hypothesize that the flowing suspension will no longer transition to the high viscosity fluid phase, and the shear stress will be insufficient to maintain the shear-jammed state, so the SLPs will erode.

FIG. 5: Shear rate (red) and average boundary stress (black) vs. time at constant applied stress $\sigma = A,D)\ 126\ \text{Pa, B,E)}\ 180\ \text{Pa, and C,F)}\ 324\ \text{Pa}$.
FIG. 6: A) Average boundary stress (black circles), $\dot{\gamma}$ (red triangles) and normal force (blue squares) for one event at $\sigma = 180$ Pa. B) Shear rate at which high stress events nucleate as a function of applied stress.

**Connection with Previous Observations:**

These results are consistent with previous observations of fluctuations in DST [32–35, 38–41], but the power of BSM to resolve the spatiotemporal dynamics of heterogeneous stresses reveals a complex and subtle evolution of those fluctuations. Larsen et al. [32] observed shear rate fluctuations similar to those in Fig. 5 with a connection to increases in normal stress, and speculated that these were due to transient periods of dilatant, solid-like behavior, with the dilatancy responsible for a breakdown of the slip layer between the flowing particles and the boundaries. Hermes et al. [40] observed that, in suspensions of corn starch particles in DST, rapid decreases in shear rate were accompanied by local deformations of the air-sample interface at the edge of the rheometer tool, and that the deformations sometimes appear static and sometimes move opposite to the direction of the flow. The surface deformations are also consistent with the existence of substantial dilatant pressure.

The interplay of dilatant pressure, surface deformations, and the presence or absence of a fluid layer between the particles and the rheometer plates suggests that boundary conditions play an important role in determining the spatiotemporal evolution of the high stress regions. While we cannot directly measure local normal stresses, they are likely of similar magnitude to the shear stress, which will produce deformations of the incompressible but compliant PDMS layer that will transiently change the gap by a few microns (i.e. a few percent). The fact that we and others see similar intermittent fluctuations in the system-averaged stress in the absence of a compliant boundary suggest that the basic phenomena is not dependent on those deformations, but the detailed evolution may be different with differing amounts of boundary compliance.

We previously reported the results of BSM measurements in the continuous shear thickening regime [16], where we found localized regions of high stress appearing intermittently at stresses above the critical stress. However, unlike the high stress regions reported here, the high stress regions in CST propagate in the flow direction with an average speed of about one-half of that of the top plate. We interpret these high stresses as arising from a high viscosity fluid phase, with approximately affine shear throughout, as opposed to the localized regions of jammed solid phases that we infer here from BSM measurements in DST. This picture is consistent with the
FIG. 7: Spatiotemporal dynamics of a high stress event at constant applied stress ($\sigma$) = 180 Pa shown in the $r - \theta$ plane, as in Fig. 3.

prediction of the mean field model of Wyart and Cates of a transition from low to high viscosity fluid phases at moderately high concentration, and a transition from fluid to jammed solid phases at still higher concentration [12]. In our previous report we also showed that close to DST, some high stress regions do not propagate, and that the tracer particles in the suspension tens of microns above the bottom plate intermittently become motionless, indicating that a localized portion in the suspension jammed into a fully solid phase [16], consistent with the behavior shown in Fig. 8. Those measurements were performed at high magnification, so we were not able to resolve the rapidly moving events that would correspond to solid regions anchored to the top plate.

These results reveal some of the complexity of the spatiotemporal dynamics of shear thickening suspensions, which, in general, will depend on the type of suspension, the boundary conditions, and the measurement geometry. In particular, curvature and shear rate gradient effects may be significant in the small tool parallel plate geometry used in this study. More generally, a full understanding of these phenomena will require continuum models that can move beyond mean-field and include descriptions of non-affine flow and associated density fluctuations, the coupling between flow, density, and stress, and the connection between dilatant pressure and suspension confinement.

SUPPLEMENTARY MATERIAL

See supplementary material for temporal evolution of stress using a custom rheometer tool in absence of PDMS film and movie captions.

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FIG. 8: Schematic of evolution of the solid-like phases (SLPs) inferred from the BSM measurements. (A) The relatively homogeneous, smoothly sheared suspension is interrupted by a gap-spanning SLP (B, blue particles), where the dilatant pressure creates direct contact between the particles and the boundaries and a resulting region of high boundary stress (green). The motion of the rheometer tool causes the SLP to fracture into two regions (C). One region remains anchored to the bottom plate (dark green spheres) and moves slowly backwards (D, E), while the upstream side moves in the direction of the flow (D, E). The increased shear rate between the SLPs and the rheometer plates causes the flowing suspension transitions to a high viscosity (frictional) fluid branch (gold particles). Both regions accumulate particles on their outer sides and split off smaller band-like regions of SLPs on their inner sides. The two large SLPs collide (F) and annihilate, leaving residual band-like structures that move with the top plate (G), which continue to generate regions of relatively large boundary stress (green).

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SUPPLEMENTARY INFORMATION

SUPPLEMENTARY VIDEO CAPTIONS

Supplementary Movie 1: Spatiotemporal dynamics of high stress events revealed by boundary stress measurements at a shear rate ($\dot{\gamma}$) = 27.3 s$^{-1}$ for $\phi = 0.56$. The movie is cropped to include only the time surrounding the two high stress events are visible in Fig. 2A (main text). The solid line and circle represents the motion and edge of the top plate, respectively.

Supplementary Movie 2: Spatiotemporal dynamics of high stress events revealed by boundary stress measurements at a shear rate ($\dot{\gamma}$) = 29.25 s$^{-1}$ for $\phi = 0.56$. The movie is cropped to include only time surrounding for three high stress events. The solid line and circle represents the motion and edge of the top plate, respectively.

Supplementary Movie 3: Spatiotemporal dynamics of boundary stresses at shear rate ($\dot{\gamma}$) = 39 s$^{-1}$ for $\phi = 0.56$. Partial movie is shown (first 100 seconds). The solid line and circle represents the motion and edge of the top plate, respectively.

Supplementary Movie 4: Spatiotemporal dynamics of boundary stresses at constant applied stress ($\sigma$) at $= 180$ Pa, for $\phi = 0.56$. The circle represents edge of the top plate.
FIG. S1: Temporal evolution of stress ($\sigma$) for different applied shear rates ($\dot{\gamma}$) A, D) 29.3 s$^{-1}$, B, E) 32.5 s$^{-1}$ and C, F) 37.4 s$^{-1}$ for $\phi = 0.56$ using the custom rheometer tool as described in the Methods, except without a PDMS film on the bottom plate.