Scaling of critical velocity for bubble raft fracture under tension

Chin-Chang Kuo and Michael Dennin

Department of Physics and Astronomy and Institute for Complex Adaptive Matter, University of California at Irvine, Irvine, California 92697-4575

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Synopsis

The behavior of materials under tension is a rich area of both fluid and solid mechanics. For simple fluids, the breakup of a liquid as it is pulled apart generally exhibits an instability driven, pinch-off type behavior. In contrast, solid materials typically exhibit various forms of fracture under tension. The interaction of these two distinct failure modes is of particular interest for complex fluids, such as foams, pastes, slurries, etc. The rheological properties of complex fluids are well-known to combine features of solid and fluid behaviors, and it is unclear how this translates to their failure under tension. In this paper, we present experimental results for a model complex fluid, a bubble raft. As expected, the system exhibits both pinch-off and fracture when subjected to elongation under constant velocity. We report on the critical velocity \( v_c \) below which pinch-off occurs and above which fracture occurs as a function of initial system width \( W \), length \( L \), bubble size \( R \), and fluid viscosity for both monodisperse and polydisperse systems. Though both exhibit a transition from pinch-off to fracture, the behavior as a function of \( L/W \) is qualitatively different for the two systems. For the polydisperse systems, the results for the critical velocity are consistent with a simple scaling law \( v_c \sim R/L = W \), where the fluid viscosity sets the typical time for bubble rearrangements \( \tau \). We show that this scaling can be understood in terms of the dynamics of local bubble rearrangements (T1 events). For the monodisperse systems, we observe a critical value for \( L/W \) below which the system only exhibits fracture.

I. INTRODUCTION

The rheological behavior of complex fluids exhibits a rich array of phenomenon due to their combination of solidlike and fluidlike properties [for example, see Bird et al. (1977); Edwards et al. (1991); Sollich et al. (1997)]. The response of these materials to applied stresses and strains raises interesting questions in areas ranging from yielding [Mason et al. (1996); Rouyer et al. (2005); Cohen et al. (2006); Möller et al. (2006, 2008); Xu and O’Hern (2006)] to shear localization [Coussot et al. (2002a, 2002b); Salmon et al. (2003); Lauridsen et al. (2004); Clancy et al. (2006); Katgert et al. (2008)],
to creep flow [Vincent-Bonnieu et al. (2006)], to stick-slip behavior [Coussot et al. (2002a, 2002b); Lauridsen et al. (2002)] and jamming [Cates et al. (1998); Liu and Nagel (1998, 2001); Trappe et al. (2001)]. The richness of their rheological response is one reason for the wide range of technological applications. Complex fluids include pastes, slurries, foams, granular materials, emulsions, and colloidal suspensions. Their applications include fire fighting, printing, paints, foods, drugs and drug delivery, cosmetics, and oil recovery. Therefore, understanding the fundamental elements of their flow behavior and the transition between different flow regimes is critical.

One of the central issues in the understanding of complex fluids is the transition between flow dominated fluidlike behavior and solidlike behavior. Recently, the study of this transition has focused on shear geometries, such as cylindrical and planar Couette flow, and cone and plate geometries. A major question in these geometries is the fundamental mechanisms governing shear localization in which flowing and nonflowing regions of materials coexist [see Dennin (2008); Schall and van Hecke (2010), and the references therein]. The coexistence of these two-states raises interesting questions in the context of jamming in complex fluids, such as the possibility of a dynamic transition between a “solid phase” and a “liquid phase” as a function of applied stress or strain. Such a transition may best be described by constitutive relations that explicitly treat each region of the material as existing in a separate phase. This is in contrast to the use of constitutive relations that are continuous as a function of external parameters, such as a Bingham plastic model. Given the wide range of shear localization that has been observed experimentally [examples include the work in Kabla and Debrégeas (2003); Coussot et al. (2002a, 2002b); Salmon et al. (2003); Lauridsen et al. (2004); Gilbreth et al. (2006); Clancy et al. (2006); Becú et al. (2006); Katgert et al. (2008); Fall et al. (2009)] and the success of various theoretical models of shear localization [examples include the work in Varnik et al. (2003); Barry et al. (2011); Møller et al. (2008); Cox and Wyn (2008); Cheddadi et al. (2008); Denkov et al. (2009)], understanding this transition between the fluid and solid behaviors is critical. The wide range of behavior points to another major question: To what degree is the fundamental physics governing the rheological properties of individual complex fluids general to all complex fluids. In addressing all of these questions, it has proven useful to focus on experimental systems that are relatively simple and serve as models for general behavior in complex fluids.

Foams have proven to be a very important model complex fluid [Kraynik and Hansen (1987); Kraynik (1988); Stavans (1993); Prud’homme and Khan (1996); Weaire and Hutzler (1999)]. One of the main reasons is the relative simplicity of the microscale physics. Foams are gas bubbles with liquid walls. In general, the main microscale forces are well understood in terms of surface tension of the fluid and internal pressure of the bubbles. This has produced a range of successful theoretical models of foam that focus on different aspects of the underlying physics [see, for example, Kraynik and Hansen (1986); Okuzono et al. (1993); Durian (1995); Hutzler et al. (1995); Jiang and Glazier (1996); Brakke (1996); Asipauskas et al. (2003); Cox (2005); Janiaud et al. (2006); Denkov et al. (2009)]. In this paper, we focus on an experimental model foam system that is quasi two-dimensional: bubble rafts.

The bubble rafts are single layers of bubbles floating on the surface of water. They have been of interest since Bragg first proposed them as a model for crystalline and amorphous systems [Bragg (1942); Bragg and Nye (1947)]. One of the advantages of the bubble raft system is the ability to directly track the motion of the bubbles under applied strains or stresses. Bubble rafts have been instrumental in studying a number of the phenomena already discussed for complex fluids. In this paper, we focus on a different class of deformations than the standard shear deformations: failure modes of a foam under applied tension.
A significant difference between solids and fluids is their response to applied tension that results in extension of the material. Typically, fluids exhibit an instability induced pinch-off. The details of the pinch-off are dependent on the fundamental properties of the fluid, such as surface tension and viscosity. However, the general behavior consists of the shrinkage of a region of the fluid until it reaches a critical width and the material breaks into one or more pieces [Shi et al. (1994); Eggers (1997)]. In contrast, most bulk solids exhibit some form of fracture under applied tension [Bouchbinder et al. (2010); Broberg (1999)]. Again, the details depend on the material and can include plastic or brittle fractures. The general behavior involves cracks nucleating in the bulk or at the boundaries and propagating through the material, breaking it into pieces. The question for foams, and other complex fluids, is whether or not one or both of these failure mechanisms occur, and if the dominant mechanism can be predicted.

For bubble rafts, initial studies reported in Arciniaga et al. (2011) established that both pinch-off and fracture were possible under conditions of a constant pulling speed. A dominant factor in determining which mode occurred was the speed at which the system was pulled. However, the system size also played a role. In this paper, we focus on the transition from pinch-off to fracture and demonstrate that this transition is controlled by the pulling speed, systems size, and time for bubble rearrangements. We present a scaling argument for the critical speed at which the system makes the transition from pinch-off to fracture.

II. EXPERIMENTAL METHODS

We utilize two experimental geometries in this study. First, the failure of the system under tension is studied using a rectangular trough in which a pair of opposite walls are pulled apart at constant speed using stepper-motors. A detailed description of the apparatus is provided in Arciniaga et al. (2011). The pulling velocities range from 0.01 to about 200 mm/s. The initial distance between the moving walls determines the initial length $L$ of the system. In our experiment, we use three initial lengths of the bubble raft: 40, 60, and 80 mm. The maximum length is limited by the overall size of the trough, the pulling speed, and the pulling distance required to generate failure. The walls are made of polycarbonate. The bubbles are observed to wet the walls. To fix the initial width, small pieces of polycarbonate of the desired width are attached to the moving walls. This creates a step edge that the bubbles do not cross. Therefore, a discrete set of initial widths from 40 to 120 mm with 20 mm steps were studied. The combinations of initial width and length provide us with 15 distinct sets of initial geometries.

The bubble raft is formed by flowing compressed nitrogen gas through a needle under a soap solution surface. The bubble size is fixed by the pressure, the needle diameter, and the needle depth under the solution. We are able to manufacture both monodisperse and polydisperse bubble rafts by this technique. The monodisperse bubble raft produces a highly ordered crystalline 2D structure within well-defined domains that are separated by grain boundaries. The polydisperse bubble raft produces a highly disordered amorphous 2D structure which is created by fixing the nitrogen pressure, the needle diameter, but oscillating the needle depth under the solution.

The structure and the dynamics of the raft are recorded using a conventional charge-coupled device (CCD) camera (Pixelink Corporation). Custom developed MATLAB programs are used to perform the image processing to characterize the individual bubble size and failure mode. The images of the typical monodisperse and polydisperse bubble rafts are illustrated in Figs. 1(a) and 1(c). Figure 1(b) shows a 2D Fourier transform pattern indicative of the ordered, hexagonal structure of the monodisperse bubble raft, whereas Fig. 1(d) shows a 2D Fourier transform indicative of the amorphous structure of the polydisperse raft.
We define the characteristic bubble radius from the peak wavevector of the angular averaged power Spectral density (PSD) of the 2D Fourier transform pattern (Fig. 2). The characteristic bubble diameter is defined by the peak position of the PSD. The bubble size distribution is defined by the full width at half maximum of the PSD peak. It is worth noting that as expected, the PSD peak is broader in the polydisperse raft than in the monodisperse raft. Upon expansion, we monitor the raft for motion out of the plane of the water surface, and the bubbles are observed to remain confined to the air–water interface.

Unlike three-dimensional foam or bubbles confined between the plates, the fact that the bubbles in a bubble raft float on the water surface allows for the existence of “voids” in the raft. A void is a region of air between the bubbles where bare water surface is present. For the polydisperse bubble raft, there can be initial voids due to the difference in bubble size. These represent a negligible fraction of total area. However, given the existence of initial voids, we use the evolution of the total void area in the bubble raft as a function of time, as in Arciniaga et al. (2011), to distinguish between pinch-off and fracture. For pinch-off, void area remains essentially zero throughout the process. Fracture is defined by a monotonic increase in void area until failure is reached. For some regions of parameter space, there is a mixed-mode where void area increases in time, but the voids “self-heal” (void area returns to zero) before failure. For the purposes of this study, we focus on the onset of fracture and define the critical velocity, \( v_c \), to be the velocity at which the void area is observed to increase with time. The existence of the mixed-mode is accounted for in the error bars reported for \( v_c \), as it does result in some uncertainty in determining the onset of fracture.
The final experimental parameter is the viscosity of the solution used to generate the bubbles. We focused on two different soap solutions: 5% Miracle Bubble, 15% glycerol, and 80% deionized water; 5% Miracle Bubble, 32% glycerol, and 63% deionized water by volume. The 32% glycerol solution has about twice the viscosity of the 15% solution. One issue for the system is the relative impact of surface tension versus the bulk viscosity of the fluid, as well as the surface viscosity of the surfactants at the interface. For the pulling speeds considered here, the bubbles remain effectively spherical at all times. Therefore, it is safe to ignore the surface tension effects. Additionally, the bubble rafts are a very wet foam, so one expects the bulk viscosity to dominate $T_1$ dynamics rather than the surface viscosity [Durand and Stone (2006); Rognon and Gray (2009)].

The viscosity was varied as a method of impacting the $T_1$ dynamics. A $T_1$ event is a topological rearrangement in a foam in which two neighboring bubbles move apart and the space is filled by two bubbles that were previously next-nearest neighbors. We use oscillatory flow to characterize the $T_1$ dynamics. The bubble raft is formed between two parallel plates, one of which is held fixed and the other is oscillated sinusoidally at constant amplitude and frequency. For sufficiently large amplitudes and low frequencies, isolated $T_1$ events are generated [see Lundberg et al. (2008) for details of the apparatus and the dynamics of $T_1$ events under oscillation]. The importance of $T_1$ events in general for flow is discussed in a number of references. Some examples are Weaire and Hutzler (1999), Dennin (2004), Cohen-Addad et al. (2004), Vaz and Cox (2005), Wang et al. (2007), Durand and Stone (2006), and Cox and Wyn (2008). Our interest is on the typical bubble speed during a $T_1$ event. We define this as $V_s = \frac{\tau}{R}$, where $\tau$ is the duration of the $T_1$ event and $R$ is the characteristic bubble radius. The duration is defined by the time between the two neighbors losing contact and the new neighbors touching. For the data reported in this paper, the $T_1$ time is measured using an amplitude of 10 mm with an oscillation frequency of 0.05 Hz. The average $T_1$ time is measured in the amorphous bubble raft. We confirmed that the typical time for a $T_1$ event was independent of the oscillation amplitude and frequency.

### III. SCALING BEHAVIOR

To derive a scaling law for the critical pulling speed, $v_c$, we start with the assumption that the $T_1$ events control the crossover from plastic flow (pinch-off) to fracture.

![Plot of the typical data of the angular averaged PSD as a function of the wavelength of the raft structure for a polydisperse raft (red dashed line) and a monodisperse raft (black line). The characteristic diameter of the bubble raft is defined as the peak position of the PSD. The characteristic bubble diameter for these systems shown here are for monodisperse bubbles, $d = 0.99$ mm, with a distribution in size given by the full width at half maximum of 0.05 mm and for polydisperse bubbles, $d = 0.94$ mm, with a distribution in size given by the full width at half maximum of 0.16 mm.]
The main premise is that the failure of a T1 event to complete generates a void in the raft that is sufficiently large that the void is able to grow in time. This is based on the experimental observation that the number of bubbles in the system is preserved. Therefore, fracture is not caused by bubbles popping, and the only other option is bubbles losing contact with their neighbors, as occurs in a failed T1 event. The argument presented here is expected to apply to a polydisperse raft, for which grain boundaries are not significant. The dynamics in monodisperse rafts is expected to be dominated by the motion of grain boundaries and dislocations. In this case, there are similarities to the T1 dominated situation, in that the motions can be decomposed into chains of T1 events. However, the motions are highly correlated, and this is expected to impact any scaling behavior.

Our proposed scaling law derives from three main ideas. First, we assume that it is reasonable to define a typical velocity for bubbles during a T1 event, \( v_s \). If the external driving force causes the bubbles to move apart faster than this typical speed, the net result is that bubbles are unable to move into the space created from the bubbles moving apart. This generates the failed T1 event that serves as the initiation of fracture. This process is illustrated schematically in Fig. 3. Second, we assume that the typical velocity of a T1 event can be decomposed into two parts based on properties of the system: (1) the radius of the bubbles \( R \) and (2) a time scale, \( \tau \), that depends on the bulk viscosity \( \eta \) of the fluid between the gas bubbles: \( v_s \sim R/\tau(\eta) \). Finally, the fact that the number of bubbles in the system is preserved, and the bubble volumes are essentially constant implies that the flow is area-preserving until voids are formed. Therefore, the divergence of the velocity field is zero, which means that

\[
\left| \frac{\partial v_x}{\partial x} \right| \sim \left| \frac{\partial v_y}{\partial y} \right|.
\]

Taking the geometry defined in Fig. 3 (lower, left corner), we have the speed in the pulling direction \( (v_x) \), the speed perpendicular to pulling \( (v_y) \), the initial length in the pulling direction \( (L) \), and the initial width perpendicular to pulling \( (W) \). Therefore, the above condition for incompressible flow gives the following relationship between \( v_x \) and \( v_y \) during the initial stages of pulling the bubble raft apart,

\[
\frac{v_x}{L} \sim \frac{v_y}{W}.
\]

For our geometry, \( v_x \) is set by the pulling speed \( v \), and \( v_y \) is set by this relation. If fracture occurs, it is in the early stage of pulling, which justifies using this relation to rewrite \( v_y \) as

\[
v_y \sim \frac{vW}{L}.
\]

As discussed, we assume that voids occur when the externally imposed velocity scale is greater than the intrinsic velocity scale for T1 events, \( v_y \geq v_s \), which sets the critical pulling velocity \( (v_x = v_c) \) from

\[
v_y \sim v_c \sim \frac{v_s W}{L}.
\]

\[\text{1There may be weak dependence of } \tau \text{ on } R \text{ as well. However, as we will show, our data are consistent with the assumption that } \tau \text{ depends only on the viscosity } \eta.\]
To test our assumption regarding the separation of \( v_s \) in terms of the bubble radius and the viscosity, we can rewrite Eq. (5) as

\[
\frac{v_c}{v_s} \sim \frac{L}{W}.
\]  

(6)

Therefore, to fully test the elements of the proposed scaling behavior, we use two separate experiments. First, we focus on the scaling of the critical velocity with bubble radius. For these experiments, we use the same fluid solution to form the raft and construct rafts with different initial geometries and bubble sizes. As we will show in the Results section, the data are consistent with a scaling of \( \frac{v_c}{R} \sim \frac{L}{W} \) with a fixed relaxation time \( \tau \). Second, we vary the viscosity of the bubble forming solutions. To measure the typical T1 velocity, we use the oscillatory experiments described in the Methods section. This allows us to test the full scaling behavior presented in Eq. (5).

IV. RESULTS

Figure 4 shows a typical polydisperse [Figs. 4(a)–4(c)] and monodisperse [Figs. 4(d)–4(f)] bubble rafts in its initial state [(a) and (d)] and at different states of failure. The initial raft length and width are 60 and 80 mm, respectively, for both cases. The pulling velocities for Fig. 4 are 2.57 mm/s for (f), 3.42 mm/s for (c) and (e), and 4.29 mm/s for (b). The images illustrate a number of the qualitative features of the fracture and pinch-off processes. First, as
expected, fracture occurs for higher pulling speed. [This was already reported in Arciniaga et al. (2011).] In general, the fracture is symmetric, as illustrated in the images, with two voids growing on either side of the system [Figs. 4(b) and 4(e)]. However, there is some variation in the initial position of the fracture, and occasionally, we observe fracture in only one side of the bubble raft. A detailed study of the fracture location will be the focus of future work and requires significantly more statistics than is currently available. One open question is whether or not the opening of voids is plastic or brittle fractures. The general shape is suggestive of plastic fracture. But, there is also the question of whether or not it is better described as a cavitation phenomena, instead of fracture. In this case, one of the key issues is whether or not the void formation can be connected to a rapid drop in pressure within the bubble raft. For the speeds studied here, the system remains well below the effective speed of sound, and our expectation is that fracture is a better model. However, the exact nature of the void opening will need to be studied in more detail.

The images also illustrate a significant difference between the monodisperse and polydisperse rafts, especially during pinch-off. The polydisperse raft experiences relatively “smooth” plastic flow, due to individual T1 events. The net result is that the boundaries of the system remain relatively smooth [Fig. 4(c)]. In contrast, the monodisperse systems “flow” by two mechanisms: discrete motions of slip along grain boundaries and motion of individual dislocations. The net result are relatively rough boundaries of the system during pinch-off [Fig. 4(f)].

Figure 5 presents the critical velocity as a function of $R$, $L$, and $W$ for bubble rafts generated from the same solution. Both the results for the monodisperse [Fig. 5(a)] and polydisperse [Fig. 5(b)] bubble rafts are presented. Three different characteristic bubble radii of 0.35, 0.47, and 0.68 mm are used. The discrete initial geometries provide 15 data sets for each bubble radius. As proposed, we scale the critical velocity by the characteristic bubble radius, and the system size is presented as $L/W$. For the polydisperse system, we
observed the proposed linear behavior. Furthermore, the collapse of the data justifies the separation of the T1 velocity in terms of the bubble radius and a separate viscosity dependent term. For the monodisperse bubble raft, the behavior is qualitatively different. We observe a minimum value of $L/W$ below which pinch-off does not occur. Also, the dependence of $v_c$ on $L/W$ is not linear. This suggests that the mechanism for fracture in the monodisperse case is fundamentally different than the polydisperse case. A comparison between the critical velocity of polydisperse and monodisperse rafts is shown in Fig. 6. In this case, we focus on the critical velocities as a function of the scaled initial width ($W/L$) for the same data sets plotted in Fig. 5. The results in Fig. 6 demonstrate that the critical velocity for the crystalline structure is lower than for the amorphous structure.

![FIG. 5. $v_c/R$ vs $L/W$ for different bubble sizes and structures. (a) is for polydisperse rafts and (b) is for monodisperse rafts. The symbols distinguish systems with different characteristic radii: 0.35 (solid squares), 0.47 (solid circles), and 0.68 mm (solid triangles). The initial lengths and widths ranged from 40 to 80 mm and 40 to 120 mm with 20 mm steps. For comparison with previous work, the insets are the same data but with $v_c/R$ vs $W/L$ plotted. The scaled critical velocities for polydisperse and monodisperse rafts collapse onto their respective master curves. However, the behavior for the two systems is fundamentally different. The fitting curves (green lines in (a) and (b)) are a linear fit for polydisperse raft (as proposed), and a polynomial fit with the second order for monodisperse raft, with an apparent onset value for $L/W$.](image)

![FIG. 6. A direct comparison for $v_c/R$ vs $W/L$ between polydisperse (black square) and monodisperse (red circle). For all the scaled initial widths, the critical velocity for polydisperse raft is larger than the monodisperse bubble raft.](image)
It should be noted that scaling proposed here is different from that used in our original work in Arciniaga et al. (2011). In Arciniaga et al. (2011), the focus was on the dependence of the critical velocity on the system width \( W \) and comparisons were made with other systems that exhibit transitions from fracture to pinch-off as a function of system size (such as metallic glass systems). Therefore, the focus was the system width in terms of the number of bubbles in the system \((W/R)\), and not the mechanism for fracture. The main result was that the critical velocity decreased with system width. The insets in [Figs. 5(a) and 5(b)] illustrate that we still observe the same dependence of critical velocity on the initial raft width. Our current work is focused on the proposed T1 mechanism and the role of \( v_s \); hence, the exploration of a different scaling behavior.

To further test the role of \( v_s \), we used solutions with different viscosities. A typical plot of the critical velocity vs the initial width is shown in Fig. 7 with 15\% and 32\% glycerol. The characteristic bubble radius is about 0.47 mm with a polydisperse bubble raft in both measurements. The only difference between these two solutions is the viscosity.

To measure \( v_s \), we measure the characteristic T1 time as described in Sec. II. The T1 time corresponds to three stages of the processes: the detaching of the connected bubbles, the intermediate state of an empty space surrounded by four nearby bubbles, and then the attaching of the next-nearest neighbor bubbles. The whole T1 process can be observed in the oscillatory shearing bubble raft with a low frequency and a large amplitude setting. The characteristic bubble radius in this experiment is about 1.2 mm for both 15\% and 32\% glycerol solutions. We use a larger bubble size than in the previous pulling apart experiment because this allows a more accurate T1 time measurement, and hence, a better measure of \( v_s \) for a given viscosity. The results for the distribution of T1 times is shown in Fig. 8(a) with 15\% glycerol and in (b) with 32\% glycerol solutions. The characteristic T1 time is defined by the average of the T1 time measurements. We find average T1 times of 0.36 and 0.47 s, respectively, for 15\% and 32\% glycerol solutions. It should be noted that this time is not directly proportional to the bulk viscosity. This is most likely due to the fact that the bubbles are interacting to some degree with the subphase as well as each other. It is know from shear flow experiments that dissipation from boundaries can be relevant [Wang et al. (2006); Janiaud et al. (2006); Katgert et al. (2008)].
Therefore, the detailed connection between viscosity and T1 velocity is presumably more complicated than a simple linear relation. Therefore, we can calculate the T1 velocity from the T1 time and the bubble radius.

Figure 9 shows the fully scaled critical velocity, \( v_c = v_s \) versus \( L/W \), where we take \( v_s \) from our oscillatory measurements. In this case, we use a polydisperse bubble raft with the range of different initial geometries (\( L \) and \( W \)) used in Fig. 5 and a characteristic bubble radius of about 0.47 mm for both 15% and 32% solutions. As expected, the data collapse for these two solutions. This result supports our scaling model which we derived in Sec. III. At this point, we recognize that the use of only two different viscosities is limited and future work will focus on exploring a wider range of viscosities and bubble radii.

**FIG. 8.** The histogram of the time for T1 events to occur in the (a) 15% and (b) 32% glycerol solutions. The T1 event time is measured by counting the time for the single T1 event in the oscillatory geometry. The histograms of 15% and 32% glycerol solution reveal an increase of the characteristic T1 time from 0.36 to 0.47 s as the viscosity is increased.

**FIG. 9.** Plot of \( v_c / v_t \) versus \( L/W \) for 15% (black squares) and 32% (red circles) solutions. The initial lengths and widths ranged from 40 to 80 mm and 40 to 120 mm with 20 mm steps. The bubble radius is about 0.47 mm for both solutions. The T1 velocity \( v_t \) is derived from the T1 time(\( \tau \)) which is measured by the oscillatory experiment.
V. SUMMARY

By varying the initial size of the bubble rafts (length $L$ and width $W$), the bubble radius $R$, and the effective time for T1 events $\tau$, we have shown that for polydisperse rafts the critical velocity $v_c$ for the transition from fracture to pinch-off is consistent with the relation: $v_c \sim L/W$, where it can be useful to separate $v_c$ into two parts and write $v_c \tau/R \sim L/W$. The derivation of this relation assumes that the T1 events control the nucleation of voids, and the experimental agreement strongly suggests that T1 events play this central role. Of particular note is the fact that the experimental results for the polydisperse system are not only linear in $L/W$, but also extrapolate to $v_c = 0$ at $L/W = 0$, which is not the case for the monodisperse system.

For monodisperse systems, the collapse of the data when $v_c$ is plotted versus $L/W$ suggests that the aspect ratio is the correct physical parameter for determining the crossover from fracture to pinch-off. However, the detailed mechanism is clearly different from that for the polydisperse case. Two interesting facts present themselves: (1) a minimum value of $L/W$ below which pinch-off is not observed and (2) consistently lower values for $v_c$ compared to the polydisperse system. Our current assumption is that grain boundaries are the source of crack nucleation in the monodisperse case based on our qualitative observation of the process. The existence of an onset for pinch-off as a function of $L/W$ suggests that for sufficiently wide systems, grain boundaries always open and nucleate cracks before the system is able to narrow significantly and pinch-off. The lower $v_c$ relative to polydisperse systems suggests that grain boundaries present a lower nucleation energy for crack formation relative to T1 events. Finally, there is the nonlinear scaling of $v_c$ with $L/W$ that requires explanation. Focusing on these issues in more detail will be the subject of future work and will be an important step forward in our understanding of the differences between crystalline and amorphous systems.

The success of our proposed scaling law for explaining the behavior in the polydisperse case has implications for generic amorphous materials, such as molecular plastics. For molecular plastic materials, there is evidence that the failure under tension is controlled by the dynamics of shear-transformation zones (STZs) [Spaepen (1977); Falk and Langer (1998); Falk (1999); Falk and Langer (2011)], which are regions of nonaffine molecular rearrangements. It is worth exploring if our arguments regarding the connection between fracture and T1 events carries over to a connection between failure modes and STZs in molecular systems. Because a T1 event is a specific, highly local event involving four bubbles and the films between them, and an STZ is a region (though relatively local) of nonaffine motion, the exact correspondence between the two types of rearrangements is still an open question. There is evidence from experiments in bubble rafts under shear that the T1 events represent the core of STZs [Dennin (2004); Twardos and Dennin (2005); Lundberg et al. (2008)]. The combination of the results presented here and the previous results for shear geometries strongly suggests that a better understanding of the connection between STZs and T1 dynamics will be important in understanding the failure of complex fluids under tension, and possible extensions to molecular systems.

Another issue that requires additional study is the scaling with the typical T1 velocity, $v_c$. At this point, we have only tested two different values of this parameter, so further work is needed in this direction. Especially of interest is the simplification of treating $v_c$ in terms of $R$ and a radius independent time scale $\tau$ associated with T1 events. It is conceivable that the scaling is based on other typical velocities formed by the ratio of $R$ and another time scale. Uniquely, distinguishing between the time scale for T1 events and other time scales requires additional work. However, at this point, the results are certainly consistent with the T1 velocity as the relevant scaling parameter.
Finally, it is worth noting that the failure of foams under over-pressure has also been studied [Arif et al. (2010)] with a focus on crack propagation. In this geometry, one also observes a velocity dependent transition between different failure modes. In this case, a transition from plastic deformation and brittle fracture is reported in Arif et al. (2010). Though there are important difference in the geometry and underlying microscopic mechanisms (such as film rupture) between the results reported here and in Arif et al. (2010), it is interesting to speculate on the potential connections between the different failure modes and the implications for complex fluids in general.

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