Collapse mechanisms and extreme deformation of particle-laden interfaces

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Abstract

Particle-laden interfaces are at the basis of many advanced materials, such as bijels and dry water. While the final properties of these materials can generally be controlled, their response to deformation during processing and use is still poorly understood. In particular, the dynamics of particle-laden interfaces in relevant flow conditions is receiving increasing attention. These conditions are typically highly dynamic and can involve unsteady flow or large deformations. This paper gives an overview of the remarkable phenomena of particle-laden interfaces undergoing deformations of large amplitude and at high strain rate, in other words extreme deformation. Upon large-amplitude compression, a monolayer of particles can collapse by buckling or by expelling particles in the liquid. The criteria for buckling or expulsions are discussed, as well as recent experiments in highly dynamic conditions showing that these criteria can depend also on the rate of deformation. The emerging use of ultrasound-driven bubbles as an experimental platform for controlled deformation of particle-laden interfaces at high strain rate is also discussed. The ability to control the fate of particles at interfaces during dynamic deformation of droplets or bubbles ultimately underpins a variety of applications from controlled release to catalysis.

Keywords: particle-laden interfaces, armoured bubbles, Pickering emulsions, interfacial rheology

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1. Introduction

Colloids at fluid interfaces continue to find new applications in advanced and functional materials, from dry water [1] and bijels [2], to capillary foams [3]. Colloidal particles are not simply alternatives to molecular surfactants, but can provide specific functionality in processes involving dispersed fluid phases [4]. For instance, drops and bubbles stabilised by functional nanoparticles can be used in interfacial catalysis [5, 6] and gas storage [7]. The stability of materials based on the self-assembly of colloids at interfaces is understood in terms of the large decrease in free energy upon particle adsorption [8], and the mechanical strength of the interface due to 2D jamming of the particles [9]. Despite the precise control that can be achieved over the structures formed by particles at fluid-fluid interfaces, our understanding of the phenomena of particle-laden interfaces undergoing deformation – such as in the flow of emulsions and foams, and the evaporation of suspensions – remains incomplete. Yet, the mechanical response of these complex interfaces is central to the processing and performance of advanced materials and other products [10].

A monolayer of colloidal particles at a fluid interface is characterised by a surface pressure, $\Pi$, which acts in the opposite direction (spreading) to the surface tension. [Figure 1(a)]. In processing flow conditions, the interface deformation will typically be a combination of both shear and dilation [Figure 1(b)], in contrast with bulk fluids that can usually be considered to be incompressible [11]. Hence a full characterisation of the interfacial properties includes surface shear elasticity and viscosity, $G^\sigma$ and $\eta^\sigma$ respectively, as well as dilational elasticity and viscosity, $K^\sigma$ and $\kappa^\sigma$ respectively. In addition, complex fluid interfaces exhibit remarkable phenomena that bear no analogy to bulk systems. Upon large-amplitude compression, structured interfaces can collapse by buckling like an elastic film, by expulsion of material into the bulk, or by forming multilayers [Figure 1(c)].

An additional challenge in studying the processability of materials based on
Figure 1: Phenomena of particle-laden fluid interfaces upon deformation. (a) Particle-laden fluid interface in equilibrium. The surface tension of the bare fluid-fluid interface is $\gamma_0$. The colloid monolayer generates a surface pressure $\Pi$. (b) Dilation is a leading-order mode of deformation of interfaces in addition to shear. The corresponding rheological properties are surface dilational elasticity and viscosity, $K^s$ and $\kappa^s$, and surface shear elasticity and viscosity, $G^s$ and $\eta^s$. (c) Compression can cause a particle-laden interface to buckle like an elastic film with bending elasticity $\kappa_b$ (top), expel material into the bulk phase (middle), or form multilayers (bottom).

The focus is mainly on experiments designed to provide simultaneous information on the microstructure formed by colloids at the interface and the macroscopic response of the interface. Insights provided by discrete particle
simulations are also discussed. Finally, monolayers of colloids at fluid interfaces can serve as useful two-dimensional models to visualise emergent phenomena in conditions of high-rate and extreme deformation of soft matter. This is an area of increasing interest with applications ranging from elastomers and nanocomposites for impact mitigation [12, 13, 14] to understanding the effect of blast injury on soft tissues [15].

2. Controlled deformation of particle-laden interfaces: link between microstructure and rheology

The properties of complex fluid interfaces can be characterised in the linear and non-linear regime through established methods of interfacial rheology [16] and tensiometry [17]. There is a growing interest in addressing the question of processability of materials based on particle-laden interfaces. For instance for bijels, links are being established with the mechanical properties of the bulk material [18, 19] and with the interfacial rheological properties [20]. Recently, it has also been shown that the interfacial rheological properties can be engineered to achieve desired product performance, in this case arrested dissolution of bubbles at low surface coverage by particles [21].

In addition to their direct relevance in applications, particle-laden interfaces are also useful two-dimensional (2D) models to visualise the structure and deformation of condensed matter. Already back in 1942, Bragg used rafts of floating bubbles as a 2D model for flow in metals, to visualize grain boundaries and plastic deformation [22]. Monolayers of colloids at liquid interfaces are a convenient model system because the particles can be resolved by optical microscopy, and the interparticle interactions can be tuned. The possibility to control electrostatic interactions between colloids and interfaces [23, 24] as well as their capillary interactions due to particle shape [25, 26] or interface curvature [27] gives access to 2D model systems ranging from colloidal crystals [28] to soft glasses [29] and gels [30]. For colloids with size below approximately 10 µm, the gravitational force is too small to cause an interface deformation
sufficient to drive capillary interactions. The ability to visualise the interfacial microstructure by optical microscopy has enabled the study of self-healing of curved colloidal crystals [31], of crystal growth [32] and freezing [33] on curved surfaces, and of dislocations under stress [34]. Particle-laden interfaces are therefore ideal systems to relate the microstructure, observed by optical microscopy, to the macroscopic mechanical response.

Figure 2: Link between microstructure and interfacial rheology. (a) Reversible plastic events under oscillatory shear. Reproduced from [35]. (b) Layering of bidisperse colloids under radially symmetric shear. Reproduced from [36]. (c) Yielding of densely packed, aggregated particle-laden interfaces. \( \Gamma \) is the fraction of the area covered by particles. Reproduced from [37]

The main property of interest for a quiescent interface is the surface pressure, \( \Pi \), which has an entropic contribution as well as a contribution from interparticle interactions [38]. The entropic contribution can be estimated, for moderate area coverage by particles, from the two-dimensional ideal-gas equation of state, \( \Pi = N \frac{A}{4} k_B T \). The resulting estimates of \( \Pi \) are small, ranging from a few mN/m for 1-nm particles, to \( 10^{-2} \) mN/m for 1-\( \mu \)m particles. The main contribution to the surface pressure is typically from interparticle interactions, for instance electrostatic repulsion [29].

The relation between microstructure and macroscopic stress during dynamic deformation has been studied in extension [39], compression [29] and shear [35]. Yielding [30] and flow-induced structure [40] of 2D colloidal gels under shear have been directly visualised. The direct, real-time visualization of the microstructure has revealed plastic rearrangements under oscillatory shear that
are not irreversible [35], see Figure 2(a). Binary mixtures of colloids have been found to undergo restructuring into concentric rings [Figure 2(b)] under continuous, radially symmetric shear flow [36]. Information on the evolution of the microstructure [Figure 2(c)] has enabled to link the effect of interparticle interactions to the interfacial viscoelasticity of monolayers [37]. An important role of the mesostructure has been identified, for instance solid-like crystalline domains of particles can flow on the interface if they are sufficiently small, resulting in macroscopic viscous response [41].

The majority of the studies relating microstructure and rheology of colloid monolayers have been limited to relatively low deformation rates, typically in the range $10^{-2} - 1 \text{ s}^{-1}$. This limitation is due to the challenge of imparting a controlled, high-rate interfacial deformation, while controlling the effects of bulk flow, and directly visualizing the microstructure with sufficient resolution. Recent work has begun to address this limitation, as described later.


Dilation or compression is a mode of deformation that for bulk liquids is only relevant near supersonic conditions. In contrast, interfacial dilation and compression is present in the majority of processes that involve dispersed fluid phases, such as evaporation or coalescence of drops, and dissolution of bubbles. Given its important role, the dilational rheology of particle-laden interfaces has been studied extensively as described in a previous review [42]. Here we focus on the phenomena that occur upon large area compression, where a particle-laden interface is said to undergo collapse, by analogy with lipid monolayers, as it deforms out of the plane of the interface.

3.1. Buckling of monolayers

Collapse upon compression is a well known phenomenon for lipid monolayers, and its importance in the performance of lung surfactants has made
it the focus of extensive research \[43\]. Buckling of lipid monolayers has been characterised extensively in Langmuir trough studies, and has been reported also for lipid-stabilised microbubbles undergoing deflation \[44\]. Buckling is a solid-like response characteristic of complex interfaces with predominantly elastic behavior. Proteins also form highly elastic monolayers that wrinkle upon compression \[45\]. Molecular dynamics simulations of lipid monolayer collapse show that buckling is followed by folding into a bilayer that can eventually form vesicles, depending on the bending modulus and line tensions \[46\].

Early demonstrations of buckling of particle monolayers were made using a sessile/pendant drop setup, where the drop area was reduced by withdrawing liquid with a syringe \[47, 48\]. A possible condition for monolayer buckling is that the surface pressure in the monolayer, $\Pi$, is such that the effective surface tension of the complex interface, $\gamma = \gamma_0 - \Pi$, with $\gamma_0$ the surface tension of the bare fluid-fluid interface, becomes zero. By directly measuring the pressure inside a particle-coated droplet of radius $R$, and measuring the surface pressure of monolayers of the same particles on a Langmuir trough, it was confirmed that in the buckled state both the Laplace pressure in the drop, $\Delta p = 2\gamma/R$, and the interfacial tension measured in the Langmuir trough are zero \[49\].

Buckling of planar monolayers of particles has been reported for a variety of systems \[50, 51, 52, 53, 54, 55\] and the effective surface tension has often been found to be non-zero at buckling. Monolayers of gold nanoparticles capped with dodecanethiol ligands were found to form local folds and then transition to a trilayer; the wavelength of the wrinkles allowed to extract the bending modulus of the monolayers and trilayers from elasticity theory \[53\]. In both cases the bending modulus was found to be low compared with a continuous elastic film of the same thickness, due to the particulate nature of the monolayers, and to the poor interlayer coupling in the trilayers, respectively. The bending modulus can affect emulsion stability if it is comparable to the energy of surface dilatation; this can be the case for close-packed monolayers, for which a theoretical expression based on the microstructural details of the monolayer has been obtained \[56\]:

$$\kappa_b = \frac{1}{2}\gamma_0 a^2 \left( \frac{3}{4} \phi_{hcp} \sin^4 \theta + 5 \cos^2 \theta - \frac{7}{8} \right) \text{ with } a \text{ the particle radius},$$
\( \phi_{\text{hcp}} \approx 0.91 \) the area fraction occupied by an hexagonal packing of spheres, and \( \theta \) the contact angle. For particles with anisotropic shape, it was found that ellipsoids can rearrange to release compressive stress through a flipping transition upon monolayer compression [51]. Expulsion of particles in the subphase was also observed in this system, and the monolayer buckled upon further compression. Experiments and simulations show that monolayers of spherocylinders buckle for small aspect ratio of the particles, while flipping of individual particles and bilayer formation is observed for large aspect ratio [57]. For particles with anisotropic surface chemistry, a comparison of homogenous polystyrene particles with gold-polystyrene Janus colloids of the same size reveals that while the homogeneous particles form monolayers that buckle upon compression, the Janus particles form bilayers upon monolayer collapse due to the anisotropic particle-particle and particle-interface interactions [55]. Monolayer collapse can be an undesirable phenomenon in the application of nanoparticle monolayers to advanced functional materials, for instance made from gold nanoparticles [58], or graphene and graphene oxide sheets [59].

Solid-like behavior of particle-laden interfaces has been observed on dissolving drops and bubbles, which are systems of direct relevance to formulated products and advanced materials processing. A range of shape transformations, including buckling and wrinkling, has been observed for nanoparticle films on droplets dissolving by solvent exchange in an external fluid phase [60]. The dissolution of bubbles coated with hydrophilic particles in water was found to lead to either buckling or expulsion of particles from the interface, depending on the ratio of the particle size to the radius of curvature of the bubble [61]. The effect of particle size relative to the radius of curvature of a bubble's interface was studied by controlling bubble volumes and measuring the internal pressure. Different regimes were revealed: from soft crumpling for small particles, to faceting and granular arches for large particles [62]. For bubbles dissolving in oil and coated with hydrophobic particles, buckling of the interface was observed [63]. In both these studies, dissolution was forced by changing the temperature so as to vary the solubility of air in the surrounding liquid. Another approach to
drive bubble dissolution and study the mechanical resistance of particle-coated bubbles has been to change the ambient pressure [34].

### 3.2. Expulsion of interfacial material

In some of the experiments described above, expulsion of particles from the monolayer was observed. The conditions for buckling versus particle expulsion are discussed here. Controlled expulsion of colloidal particles from the interfaces of drops or bubbles offers the potential for programmable particle delivery in biomedical applications, and recovery of functional particles for regeneration and reuse in processes. It is therefore important to understand the conditions for expulsion in relation to particle size, contact angle and interparticle interactions. Other mechanisms have been reported for particle removal from interfaces that are not caused by an interface deformation, for instance due to changes in surface free energy of the particles [64].

A simple argument can be made that the energy cost to expel one particle [8], \( \Delta E = \gamma_0 \pi a^2 (1 \pm \cos \theta)^2 \) must be provided through the mechanical work, \( dW = \Pi dA \), made upon interface compression. Equating \( dW \) to \( \Delta E \) with \( dA = \pi a^2 \) the cross-sectional area of the particle gives the condition \( \Pi = \gamma_0 (1 \pm \cos \theta)^2 \), independent of the particle size, and dependent only on the pair of fluids and the wettability of the particle. If the contact angle approaches 90°, then the surface pressure needs to increase up to \( \Pi = \gamma_0 \), at which point the monolayer should buckle instead of expelling particles. This argument however does not take into account the effect of attractive interparticle interactions. If attractive interparticle interactions are dominant, then the particles form a cohesive monolayer, and the system will always behave as an elastic film with solid-like behavior, and buckle upon compression [38].

The conditions for particle expulsion have been tested in several experiments. Using glass beads of different wettability at the air-water and water-octane interface, it was shown that particles that are wetted by the aqueous subphase (\( \theta < 40^\circ \), with \( \theta \) measured in the water phase) are expelled, while particles with partial wetting (high \( \theta \)) form monolayers that buckle [65]. The difference
was ascribed in part to the effect of attractive interactions between hydrophobic particles in contact with an aqueous subphase. This is consistent also with the observation that monolayers of dodecanethiol-capped gold nanoparticles on polar subphases (high $\theta$) undergo buckling [53]. In contrast, nanoparticles capped with amphiphilic ligands at the interface of water with a fluorinated oil can exhibit short-range, soft repulsion [66] that enable expulsion of the particles upon interface compression [67]. Simultaneous pendant drop tensiometry and grazing-incidence small-angle X-ray scattering (GISAXS) on the same system showed that the collapse behavior of the monolayer depends on the rate of compression [68]. The collapse pressure decreases with increasing compression rate. Interparticle distances obtained from GISAXS suggest that for slow compression the nanoparticles can attain a higher surface concentration by rearranging in the plane of the interface, while intra-layer stress relaxation is inhibited for fast compression and the particles re-organize out of the plane of the interface.

The effect of particle wettability and electrolyte concentration on the collapse mechanisms of silica microparticles at the water-air interface has been explored in Langmuir trough experiments [54]. For hydrophobic particles, collapse of the monolayer occurs through buckling, followed by reversible folding without particle expulsion. Unfolding of the monolayer upon re-expansion occurs at constant surface pressure, as shown in Figure 3(a). Moderately hydrophilic particles are expelled in the subphase upon compression, and therefore the surface pressure upon re-expansion is much lower than upon compression, as shown in Figure 3(b). Optical micrographs taken after re-expansion of the monolayers show large particle rafts indicative of strong interparticle attraction [inset in Figure 3(a)], and small dispersed clusters indicative of weak attraction [inset in Figure 3(b)], respectively. The addition of electrolyte was found to have a more significant influence on less hydrophobic particles, because of screening of interparticle electrostatic repulsion.

Simulation studies offer additional insights into the microscopic mechanisms of collapse of particle monolayers. Brownian dynamics simulations were used to explore the effect of interparticle interactions on particle expulsion from a
Figure 3: **Buckling versus particle expulsion upon monolayer collapse.** (a) A monolayer of hydrophobic particles at the water-air interface collapses by buckling and folding. The folds are reversible and the surface pressure remains constant during unfolding upon re-expansion. Adapted from [54]. (b) Moderately hydrophilic particles are expelled from the monolayer during compression, and the surface pressure during re-expansion is lower than during compression. Adapted from [54]. (c) Simulations capturing the particle position relative to the interface as well as interface deformation during compression show buckling or expulsion depending on the particle properties. The particle position is color-coded on a scale from blue (particle at the interface) to red (particle expelled in the fluid). Adapted from [69]. (d) Dissipative particle dynamics simulations capture the distribution of contact angles of particles at the interface of a dissolving droplet. Adapted from [70].

Discrete particle simulations that accurately capture the interface deformation revealed a transition from buckling to particle expulsion [Figure 3(c)] depending on $\Pi/\gamma_0$, on the ratio $a/R$ of the particle size and the radius of curvature of the interface, and on the strength of adhesion of the particles to the interface [69]. In these simulations it was found that large values of $a/R$ correlated with higher probability of desorption due to the comparatively large normal component of the contact force between the particles (which is proportional to $1/R$). It was also found that, in the absence of bending rigidity, buckling requires $\Pi/\gamma_0 = 1$, while desorption can occur for $\Pi/\gamma_0 < 1$, depending
on the contact angle. Dissipative particle dynamics simulations of nanoparticles at the interface of a dissolving droplet [70] reveal a bimodal distribution of contact angles characteristic of a bilayer, as shown in Figure 3(d).

4. Extreme deformation: high-rate or unsteady

Processing flows are characterized by high strain rates because of large fluid velocities in small gaps, and can be highly unsteady due to periodic forcing and turbulence. Drops and films can break up or coalesce on fast time scales. The behavior of particle-laden interfaces in such flow conditions remains largely unexplored. Initial progress in this area points to the fact that unexpected phenomena can emerge upon highly unsteady deformation. For instance inertia of very small particles, typically negligible, can become important because the fluid undergoes large accelerations. Flow-induced microstructure can arise due to periodic forcing that is much faster than the relaxation timescale of the system, leading to unexpected collective behaviors and large transient stresses. Hydrodynamic interactions between colloids at interfaces can affect their assembly upon dynamic interface deformation. The dynamics of particle-laden fluid interface is indeed an emerging research area with already several examples of interesting phenomena, described below.

4.1. Ultrafast deformation

The behaviour of particle monolayers under deformations faster than the typical time scales of interfacial rheology experiments, $10^{-2} - 1 \text{ s}^{-1}$, remains difficult to investigate. This is mostly due to the experimental challenge of simultaneously imparting dynamic deformations and visualizing rearrangements of the microstructure. Recently, experiments combining high-speed video microscopy with methods to impart controlled deformations at high rate have begun to cast light on this regime of deformation.

Acoustic excitation of bubbles has emerged as a method to impart controlled, ultrafast deformation of gas-liquid interfaces. In the oscillating pressure field
caused by the acoustic wave, a gas bubble undergoes periodic compression and expansion at the frequency of the acoustic wave. If the bubble remains spherical, the interface deformation is pure dilation. The natural frequency of the bubble, for which the bubble responds most efficiently, depends on the bubble size, as well as on the rheological properties of the surrounding fluid and of the interface \[72\]. The range of deformation rates \(10^3 - 10^6 \text{ s}^{-1}\) can be accessed using ultrasonic excitation of bubbles from micrometers to millimeters in size.

Early demonstrations of this method have been presented for biomedical microbubbles for ultrasound imaging, which are stabilised by a phospholipid monolayer. Buckling of a phospholipid monolayer on a microbubble undergoing compression at \(10^6 \text{ s}^{-1}\) was imaged using high-speed imaging at 15 million frames per second [Figure 4(a)]. The bubble of 3 \(\mu\text{m}\) in radius was driven into oscillatory compression and expansion by ultrasound at 1 MHz. Expulsion of phospholipids was also imaged using high-speed fluorescence \[73\]. A range of phenomena of particle-laden interfaces has been reported for particle-coated bubbles driven by ultrasound. Monolayer buckling \[74\] and particle expulsion \[74, 75\] have been observed for compression rates of \(10^4 - 10^5 \text{ s}^{-1}\). Here, bubbles of tens to hundreds of micrometers in size were excited by ultrasound in the range 10-100 kHz. Interestingly, upon highly dynamic deformation, particle expulsion occurs even for initially cohesive monolayers, because the mechanical energy input to the monolayer is sufficient to re-disperse the particles on the interface \[74\]. On a larger scale, millimetric particle-coated bubbles with initial anisotropic shapes were found to relax to their equilibrium spherical shape when vibrated, with the excess particles expelled in the surrounding liquid \[76\]. Sustained non-spherical oscillations due to shape instabilities of particle-coated bubbles were also reported \[77, 75\]. In this case, particle expulsion is localized at the antinodes of the shape oscillations [Figure 4(b)], where both the rate of change of area and the interface acceleration are a maximum. In particular, due to the high oscillation frequency, the maximum acceleration normal to the interface is in the range \(10^5 - 10^6 \text{ m s}^{-1}\). This observation points to a synergistic contribution to particle expulsion from the tangential stress \(\Pi\), and from
the inertia of the colloids which becomes non-negligible for such large accelerations. Another indirect evidence of the effect of inertia of colloidal particles in these systems is the observation of dynamic capillary interactions [78], which drives the formation of transient microstructures that have no counterpart at low strain rate.

These dynamic phenomena may be important in determining the behavior of particle-coated drops and bubbles undergoing large, unsteady deformation in processing flow conditions. Direct visualization of drop deformation in microfluidic extensional flow shows extreme drop deformation [79], with highly inhomogeneous interface deformation and local crumpling of the particle monolayer [Figure 4(b)]. Another remarkable example of extreme deformation of colloid monolayers, albeit not confined at a liquid interface, is impact propagation achieved by exciting a target particle via pulsed-laser ablation. At the remarkably high strain rates resulting from impact propagation, approaching $10^9 \text{ s}^{-1}$, elastic collisions between colloidal particles were found to become important [80].

4.2. Coalescence

Drop or bubble coalescence is an important phenomenon in processing flows that is accompanied by significant interface deformation. Stabilization of so-called Pickering emulsions by particles is known to be very effective, and to largely prevent coalescence [8]. Depending on the initial surface coverage by particles, the monolayer can completely prevent coalescence, or arrest coalescence in an intermediate shape after contact of two droplets [82]. When coalescence does occur, the interface deformations are very unsteady. The fate of particle monolayers during controlled coalescence of two particle-laden interfaces has been studied in some detail to better understand the conditions for stability. The coalescence of particle-coated drops with planar interfaces has been studied to visualize the evolution of the contact area [83] and to determine the velocity threshold for coalescence under impact [84]. The damped, oscillatory dynamics after coalescence is affected by the interfacial rheology of the particle monolayer.
Figure 4: Extreme deformation of particle monolayers. (a) Buckling of a phospholipid-coated microbubble undergoing compression at a rate of $10^6 \text{ s}^{-1}$. Reproduced from [81]. (b) Directional particle expulsion from particle-coated bubbles undergoing shape oscillations in ultrasound at 50 kHz. Adapted from [74]. (c) Buckling and crumpling of nanoparticle-coated droplets in microfluidic extensional flow. Reproduced from [79]. (d) Impact propagation in a dense colloid monolayer excited by a laser ablation pulse, with (e) propagation velocity of up to 1 m s$^{-1}$. Adapted from [80].

Because of the interfacial area reduction after coalescence of two drops, it is expected that particles can also be expelled in the bulk fluid. In experiments on bubble coalescence it was found that particle expulsion was largely independent of the properties of the particles, indicating that expulsion in this case is dominated by the kinetic energy generated by the coalescing bubbles [86]. This is another interesting example of the important role of dynamic effects when the conditions deviate from well-characterized, quasi-static deformations.

5. Conclusions and perspectives

Multiphase systems with particle-laden interfaces need to be characterized on different time scales in order to control their behavior in applications. Our understanding of the quasi-static conditions for particle adsorption and of interparticle interactions is rather satisfactory. This understanding has been successfully applied to design a range of products and advanced materials. The
collapse mechanisms of monolayers of colloidal particles have also been qualitatively linked to the properties of the particles and the fluid phases. An aspect that has recently begun to receive increasing attention is the processing of multiphase systems with particle-laden interfaces. A better understanding of the dynamic deformation of particle-laden interfaces is still needed. Significant efforts have been devoted to the characterization of the interfacial rheological properties of particle-laden interfaces. However most controlled experiments are limited to small-amplitude or slow deformations that are not representative of processing flow conditions. The few existing experiments on monolayer collapse during fast deformation show that the conditions are very different from the quasi-static case. Dynamics effects, such as inertia of the particles and hydrodynamic interactions, become important and can change the qualitative behavior. It is therefore anticipated that this will become and increasingly active area of research requiring an interdisciplinary effort from different communities, from colloid and interface science to fluid dynamics.

Conflict of interest

The author declares no conflict of interest.

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References


[54] S. Razavi, K. D. Cao, B. Lin, K. Y. C. Lee, R. S. Tu, I. Kretzschmar, Collapse of particle-laden interfaces under compression: Buckling vs par-


24


