COLLOID SCIENCE

Non-spherical bubbles

Surface tension gives gas bubbles their perfect spherical shape by minimizing the surface area for a given volume[1]. Here we show that gas bubbles and liquid drops can exist in stable, non-spherical shapes if the surface is covered, or 'armoured', with a close-packed monolayer of particles. When two spherical armoured bubbles are fused, jamming of the particles on the interface supports the unequal stresses that are necessary to stabilize a non-spherical shape.

We have previously described a microfluidic method for producing spherical armoured bubbles that are all the same size[2]. The rigid particles straddle the gas–liquid interface and have mechanical properties distinct from either constituent, forming what we call an interfacial composite material.

We find that fusion of these armoured bubbles, achieved by squeezing the bubbles between two glass plates, produces a stable ellipsoidal shape (Fig. 1 a–c) (for methods, see supplementary information). The fused armoured bubble is unable to relax to a spherical shape by expelling particles: instead, the jamming[2] of the particles on the closed interface, which is mediated by surface tension, leads to non-minimal shapes.

The non-trivial geometry of these bubbles provides a natural means of understanding the state of stress in the interfacial composite material. A balance of normal stresses at the bubble surface demands that

$$\Delta P = \frac{\sigma_1}{R_1} + \frac{\sigma_2}{R_2}$$

where ΔP is the pressure jump across the surface, R_1 and R_2 are the local principal radii of curvature, and σ_1 and σ_2 are the corresponding principal resultants of surface stress. Therefore, if $R_1 \neq R_2$, as is the case for non-spherical bubbles, then $\sigma_1 \neq \sigma_2$. A simple fluid interface at equilibrium cannot support unequal stresses[3]. But the bubble does, because of steric jamming[4] of the armour particles, so we term the interfacial composite material a solid.

The armoured bubbles can be remodelled into various stable anisotropic shapes because the interfacial composite material is able to undergo extensive particle-scale rearrangements in order to accommodate external inhomogeneous stresses (our manuscript in preparation). These shape changes occur with apparently no hysteresis and at relatively low forces, which is equivalent to perfect plasticity in continuum mechanics.

High aspect-ratio shapes with saddle curvature can be maintained on the armoured bubbles (Fig. 1d). This feature may be exploited to change the topology of the bubble by introducing a hole into the object, thereby creating a stable genus-1 toroid (Fig. 1e). The change in topology is irreversible[5], and seems to be the only permanent change associated with the manipulation of the interfacial composite material.

We have found that interfacial jamming is a general phenomenon that occurs with particle types such as polymethylmethacrylate, gold and zirconium oxide, and that spans four orders of magnitude in particle and bubble sizes. Similar effects are evident with liquid droplets of mineral oil that are covered with rigid particles (Fig. 1f).

Stable, non-spherical shapes of pressurized systems that have no obvious source of a stress-bearing network have been reported for dirty air bubbles in the ocean[6] and for various cellular organelles[7]. Also, systems such as gelled lipids on air bubbles[8] and protein-coated vesicles[9] show plasticity. We propose that a generic interfacial jamming transition may explain the mechanical properties and structural stability of these diverse systems.

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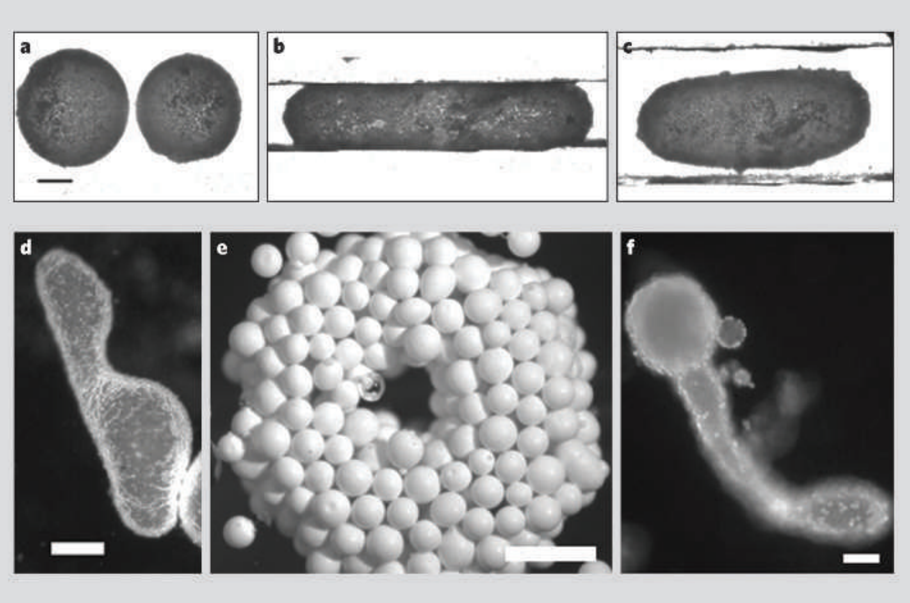

Figure 1 | Non-spherical gas bubbles. In **a–d**, the bubbles are covered with charge-stabilized, fluorescent polystyrene beads, each of 2.6 μm diameter. **a,** Two initially spherical armoured bubbles. **b,** The bubbles are compressed between two glass plates (see supplementary information for details), which exposes naked interfaces that spontaneously coalesce. **c,** The gas bubble maintains a stable ellipsoidal shape even after the side plates are removed. **d,** Armoured bubble with a stable saddle shape. **e,** The ability to maintain a saddle curvature allows a hole to be introduced into the bubble to create a permanent change of topology into a genus-1 toroid; here the particles are ground zirconium, of average diameter 200 μm. **f,** Non-spherical shapes can be similarly maintained on mineral-oil droplets in water armoured with 4.0-μm fluorescent polystyrene particles.
Scale bars (μm): **a–c**, 100; **d**, 200; **e**, 500; and **f**, 16.

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ERRATUM

Nanoscale hydrodynamics: Enhanced flow in carbon nanotubes

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In Table 1, slip lengths are in micrometres (and not millimetres, as published).
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