Preparation of Aqueous Core/Polymer Shell Microcapsules by Internal Phase Separation

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Abstract

Aqueous core/polymer shell microcapsules with mononuclear and polynuclear core morphologies have been formed by internal phase separation from water-in-oil emulsions. The water-in-oil emulsions were prepared with the shell polymer dissolved in the aqueous phase by adding a low boiling point cosolvent. Subsequent removal of this cosolvent (by evaporation) leads to phase separation of the polymer and, if the spreading conditions are correct, formation of a polymer shell encapsulating the aqueous core. Poly(tetrahydrofuran) (PTHF) shell/aqueous core microcapsules, with a single (mononuclear) core, have been prepared, but the low Tg (−84 °C) of PTHF makes characterization of the particles more difficult. Poly(methyl methacrylate) and poly(isobutyl methacrylate) have higher Tg values (105 and 55 °C, respectively) and can be dissolved in water at sufficiently high acetone concentrations, but evaporation of the acetone from the emulsion droplets in these cases mostly resulted in polynuclear capsules, that is, having cores with many very small water droplets contained within the polymer matrix. Microcapsules with fewer, larger aqueous droplets in the core could be produced by reducing the rate of evaporation of the acetone. A possible mechanism for the formation of these polynuclear cores is suggested. These microcapsules were prepared dispersed in an oil-continuous phase. They could, however, be successfully transferred to a water-continuous phase, using a simple centrifugation technique. In this way, microcapsules with aqueous cores, dispersed in an aqueous medium, could be made. It would appear that a real challenge with the water-core systems, compared to the previous oil-core systems, is to obtain the correct order of magnitude of the three interfacial tensions, between the polymer, the aqueous phase, and the continuous oil phase; these control the spreading conditions necessary to produce shells rather than “acorns”.

Introduction

The use of various kinds of colloidal systems for encapsulation of “active ingredients” has received considerable scientific interest in recent years due to the many advantages afforded by these encapsulated systems.1 For example, encapsulation may allow the safe handling of toxic materials, increase the shelf life of an active material (by reducing, e.g., hydrolysis or oxidation reactions), masking of distasteful flavors in food products, and control of release rates. This has led to encapsulation technologies finding application in areas as diverse as agriculture, drug delivery, food technology, detergency, and cosmetics.2

While traditional colloidal systems, such as liposomes, micelles, emulsions, and gel particles, can be used for encapsulation, the inability to finely control the release profile limits their usefulness.3 Microspheres, which are solid particles having the active ingredient dispersed homogeneously throughout the matrix, have greater potential, particularly for sustained release. However, microspheres are not as useful in situations where the active ingredient is required to be released rapidly upon applying some form of “trigger” such as a change in temperature or pH.2

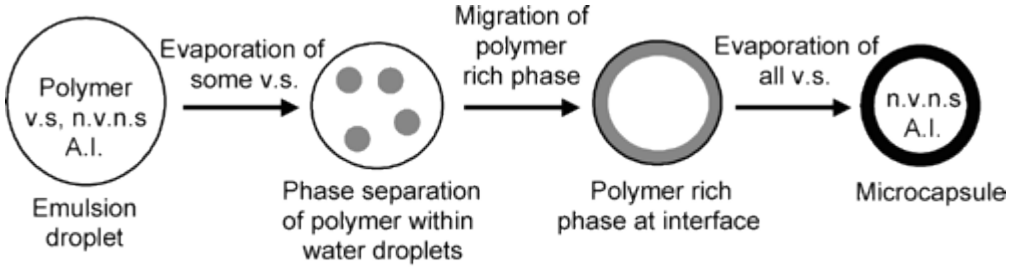
Microcapsules having a polymeric shell and a liquid core offer greater versatility for encapsulation and triggered release applications. Microcapsules of this type range in size from less than a micron (nanocapsules) to a few millimeters. Chemical functionality or biocompatibility can be achieved through the use of an appropriate shell polymer. The shell can be made controllably permeable using a suitable trigger, such as pH, ionic strength, osmotic pressure, or temperature, facilitating controlled release.4,5 For sustained release applications, the polymer shell of the microcapsule swells upon triggering, slowly releasing the active ingredient. In this case release is controlled by the rate of diffusion of the active ingredient through the shell and hence determined by the shell thickness and the degree of shell swelling.6-9 Alternatively, the capsules can deliver an active component via a differential osmotic pressure release mechanism, where the shell is ruptured by solvent ingress into the core to release the contents. The release kinetics in this case are controlled by the mechanical strength of the shell wall.10-12

The established methods by which microcapsules are commonly synthesized not only limit the choice of shell polymer but also result in irregularly shaped capsules with nonuniform, thin walls. This variability makes predicting release from the microcapsules difficult. Perhaps the most common method of producing microcapsules is via interfacial step-growth polymerization, whereby a monomer in the continuous phase of an emulsion reacts with a second monomer in the dispersed phase.13-16 The polymer forms at the interface. As the polymerization reaction proceeds, the reaction rate decreases. Unfortunately, therefore, this route generally produces microcapsules with thin shells, and also unreacted monomer may remain present in the core as an impurity. Alternatively, shells may be formed by the controlled precipitation of a polymer, or mixture of polymers, from the continuous phase of an emulsion at the droplet interface.17-20 This process is limited to polymers that are initially soluble in the continuous phase and can result in irregular microcapsules with nonuniform shell thickness. A recent innovation for the preparation of microcapsules is the multistep, layer-by-layer adsorption strategy,3,21 in which a solid particle (or oil droplet) is used as a template, onto which, in the first step, a polyelectrolyte of opposite charge is adsorbed. This is followed by the sequential adsorption of alternate layers of oppositely charged polyelectrolytes; this allows precise control of the total thickness of the shell. If desired, the solid core may then be dissolved out, allowing water to penetrate. By then swelling the polymer shell, diffusion of active ingredients into the core can be effected. If the shell is subsequently collapsed again, encapsulation of the active ingredient may be achieved. The control this method permits over

the layer thickness and degree of swelling allows the release profile to be finely tuned. A major disadvantage is simply the large number of steps required to form the microcapsules.

This research group has developed a method of producing microcapsules in which the shell is formed by phase separation of the polymer from within oil/water emulsion droplets.22-24 The dispersed oil phase consists of the (wall-forming) polymer dissolved in a mixture of a high boiling point, good solvent and a low boiling point, poor solvent. When the good solvent is removed, the previously dissolved polymer separates from the remaining poor solvent. If the balance of the interfacial tensions is correct, the polymer forms a shell at the oil droplet/water interface. This mechanism is presented schematically in Figure 1.

Figure 1 Schematic representation of the mechanism of microcapsule formation by internal phase separation.



n.v.n.s. = non-volatile non-solvent; v.s. = volatile solvent; A.I. = active ingredient.

The necessary conditions for microcapsule formation can be determined by considering the various interfacial tensions between the (shell) polymer (p), the oil phase (o), and the continuous water phase (w), i.e., γop, γow, and γpw. Torza and Mason25 have analyzed the various possible equilibrium morphologies adopted by droplets of immiscible liquids (phases 1 and 3) when brought into contact with a third mutually immiscible liquid (phase 2), again in terms of the various interfacial tensions between the phases (γ12, γ23, and γ13). By defining the spreading coefficients for each phase as

$$S_i = \gamma_{jk} - (\gamma_{ij} + \gamma_{ik}) \qquad (1)$$

and designating phase 1 to be that for which γ12 > γ13, then S1 < 0 and there are only three possible combinations of Si:

$$S_1 < 0; \quad S_2 < 0; \quad S_3 > 0 \qquad (2)$$

$$S_1 < 0; \quad S_2 < 0; \quad S_3 < 0 \qquad (3)$$

$$S_1 < 0; \quad S_2 > 0; \quad S_3 < 0 \qquad (4)$$

When the conditions of eq 2 are satisfied, core−shell particles are formed, with phase 1 appearing as the core within a shell of phase 3. When eq 3 is satisfied, “acorn”-shaped particles are formed, and when eq 4 is satisfied, two separate droplets are formed.

Loxley and Vincent22 had previously prepared microcapsules with poly(methyl methacrylate) shells and hexadecane cores using this internal phase separation route, starting from oil-in-water emulsions. The oil core microcapsules produced were spherical and had reasonably narrow size distributions and controllable shell thickness, with thick shells (up to 10% of the particle radius) easily produced. These properties make the release profile predictable and tunable.23 It has been shown that if further control of the rate of release is required, the polymer shell can be cross-linked or a second polymer layer adsorbed to the primary shell, after the capsule has been formed.24

By way of contrast to microcapsules with oil cores, there have been relatively few papers detailing the preparation of microcapsules with aqueous cores during recent years.26-32 Traditionally, the encapsulation of water-soluble active ingredients in microcapsules has often been accomplished by the use of water-in-oil-in-water multiple emulsions.30-32 However, the amount of any water-soluble active ingredient in the internal aqueous phase is necessarily lower in such multiple emulsion droplets, compared to microcapsules of a similar size, but having a single aqueous core.

In this paper we present a method for the preparation of microcapsules with aqueous cores using the "inverse" of the method described for oil-core microcapsules. A water/oil emulsion is prepared, with the shell polymer dissolved in the aqueous phase using a low boiling point cosolvent. Removal of the cosolvent leads to formation of a polymer shell. If desired, the resultant microcapsules may be redispersed in water to give aqueous core/polymer shell microcapsules dispersed in an aqueous continuous phase.

Experimental Section

The following chemicals were obtained from Aldrich and used without further purification, unless otherwise stated: polytetrahydrofuran (PTHF) Mn ca. 2900; poly(methyl methacrylate) (PMMA) Mw ~ 15 000; poly(isobutyl methacrylate) (PIBMA) Mw ca. 130 000; sorbitan monooleate (Span 80); heavy white mineral oil; hexadecane; acetone 99.5%; Brij 35; fluorescein; alumina. All purities were >97%. Deionized water (Purite) was used for the aqueous phase. Oils were purified by repeated passage over an alumina column prior to use.

The basic method used for preparation of core−shell particles by internal phase separation has been previously described in detail by Loxley and Vincent22 and was adapted here for the preparation of aqueous core microcapsules. Briefly, the required mass of polymer (0.125−1 g) was dissolved in a mixture of acetone (12−20 g) and water (1 g). The required mass of emulsifier (0.5−10 wt % of the oil phase) was added to 103 g of oil, either heavy mineral oil or hexadecane, heated to 60 °C to ensure dissolution, and then placed in a 200 mL jacketed glass vessel, thermostated at 20 °C. This oil solution was sheared using a Silverson L4RT stirrer at speeds between 800 and 4000 rpm, depending on the desired droplet size. The aqueous phase was slowly added (over a 60 s period) to the oil to form a water/oil emulsion. Emulsification was performed for approximately 30 min. The polymer shell was precipitated by removal of the acetone using a rotary evaporator.

The final morphology of the microcapsules was investigated using optical and electron microscopy. A Nikon Optiphot microscope, fitted with Nikon 320 and 340 objective lenses, was used to characterize the capsules. Generally, a sample of the microcapsules suspended in oil was placed on a microscope slide and observed, but in some cases the microscope coverslip was depressed into the slide to rupture the capsules. This allowed the inner morphology of the capsules to be observed. Other variations to this method are noted later in the following Results and Discussion section. More detailed structure of the microcapsules was obtained using a Hitachi S-2300 scanning electron microscope (SEM). A drop of the microcapsule that had been redispersed in an aqueous surfactant solution (see later for details) was placed on a stainless steel SEM stub and allowed to air-dry overnight. The dried sample was gold-coated in an Edwards S150A sputter-coater. The chamber was evacuated to a pressure of approximately 0.8 kPa, and a sputtering current of 20 mA was applied for 4 min, giving a gold coating with a thickness of approximately 10 nm. To examine the morphology of

the core, the microcapsules were fractured prior to gold-coating by applying direct pressure with a clean, round-tipped glass rod.

Results and Discussion

To prepare aqueous core microcapsules by internal phase separation, the properties of each component of the emulsion must be carefully considered. As the poor polymer solvent is water, the good solvent must be water-miscible, solvate the polymer in the presence of water, and have a boiling point significantly less than that of water. Furthermore, as the mechanism of capsule formation is reliant on maintaining a high interfacial tension between the aqueous and oil phases, potential solvents that are surface active such as alcohols will probably not be suitable for use with this method. This was demonstrated previously, by this group, to be the case for microcapsules with oil cores.23

The microcapsules discussed here were formed from systems using acetone as the good polymer solvent: it has a low boiling point (55 °C), good water miscibility, and relatively low surface activity. Any potential shell polymer must be soluble in acetone−water mixtures, beyond a given acetone concentration, but become insoluble when the acetone is removed as well as being insoluble in the oil phase. Several polymers were identified that have the required properties and were used in this work: poly(tetrahydrofuran) (PTHF), poly(methyl methacrylate) (PMMA), and poly(isobutyl methacrylate) (PIBMA).

For each of these polymers, the minimum mass ratio of acetone to water required to dissolve the polymer is 12:1. Therefore, rather than a typical water-in-oil emulsion, it is essentially an acetone-in-oil emulsion that must be formed initially. To our knowledge, only one previous study detailing the preparation of acetone-in-oil emulsions has been reported in the open literature,33 and this method was adapted here for the preparation of the initial emulsion. When the acetone was removed, the overall mass of the aqueous phase was greatly reduced, and the water was encapsulated by polymer. Below we report on the structure of the microcapsules formed with the three different polymers.

1. PTHF Microcapsules. Initially, emulsions were prepared using heavy mineral oil, a Span 80 concentration of 9 wt %, and a shear speed of 4000 rpm. The appearance of the systems was monitored, before and after acetone removal, using the light microscope. Prior to acetone removal, the emulsion droplets were quite stable, although coalescence was occasionally noted. After the acetone was removed, the resultant particles were smaller than the original droplets, and observed collisions did not lead to coalescence. However, the small size of the particles hindered optical characterization. Therefore, in an attempt to observe the particle structure in more detail, the emulsion droplet size was increased by reducing the Span 80 concentration and the shear speed. Emulsions, produced at a shear speed of the order of 1000 rpm and Span 80 concentrations of 1.5%, had relatively large droplet sizes, of the order of 50 μm. Optical microscopy showed that these emulsions were quite polydisperse and more susceptible to coalescence than the smaller droplets. Subsequent acetone removal (under reduced pressure) required 20−30 min, leading to microcapsules.

The actual process of microcapsule formation, with these larger size droplets, was followed directly using the light microscope. A sample of the emulsion was placed on a microscope slide, but a coverslip was not used to allow rapid acetone evaporation. A series of pictures presented in Figure 2 show the change in appearance of a droplet over a time period of approximately 30 s and bare a

striking similarity to the mechanism proposed in Figure 1. In Figure 2a, as the solubility of the polymer is reduced, some droplet nucleation is apparent. Formation of larger, polymer phase droplets ensues, as seen in Figure 2b. These droplets migrate to the oil water interface, encapsulating the aqueous core, as shown in Figure 2c. At this time, the interfacial polymer phase has some acetone content and is quite fluid, so may readily adapt to the changing volume of the core. Actual shell formation presumably occurs once all the acetone has been removed.

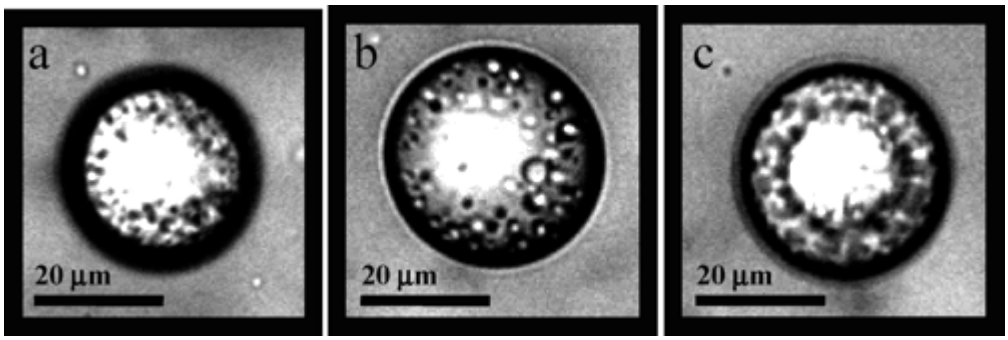


Figure 2 Optical micrographs of the change in appearance of a droplet during acetone evaporation. The continuous phase was mineral oil with 1 wt % Span 80, and the dispersed phase contained water, acetone, and PTHF. The three images were obtained over a period of about 30 s.

In the above studies the acetone was allowed to evaporate under ambient conditions. More generally, microcapsules were formed by removing the acetone under reduced pressure. Figure 3a shows microcapsules in slightly different optical planes, so their appearances are somewhat different. However, for any focal plane where the microcapsules could be clearly observed, the core−wall morphology was clear. Collisions between microcapsules did not lead to coalescence, also confirming the presence of a wall. Figure 3b shows an optical micrograph of a microcapsule that has been cooled to −15 °C. The appearance of the core would suggest frozen water; at any rate the core is clearly different from those depicted in Figure 3a. Moreover, the size of the microcapsule was observed to decrease as the microcapsule core thawed upon warming. This “elastic” behavior of the polymer shell may be attributed to the low Tg of PTHF.

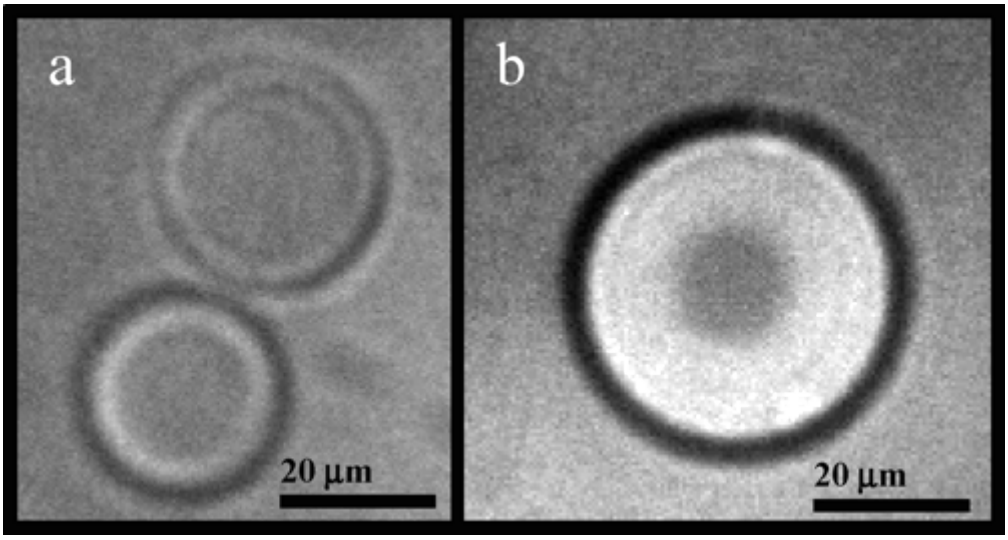


Figure 3 Optical micrographs of PTHF microcapsules: (a) two microcapsules in slightly different optical planes; (b) a microcapsule that has been cooled to −15 °C.

Further experiments were conducted to check that a polymer sheath had indeed formed around the remaining water. By pushing the coverslip into the microscope slide, the microcapsules were ruptured. Remnants of the broken PTHF shells floated and collected against the coverslip, while water droplets sank to the bottom of the oil phase, accumulating into larger droplets. Fluorescein dye was added to the aqueous phase initially, and when the microcapsules were allowed to settle over a period of a few days, the presence of the dye in the polymer walls was clear under the microscope. Finally, in instances where the encapsulation procedure failed, water collected at the bottom of the mixing vessel, which could not be detected when microcapsules had formed.

Attempts were made to transfer the microcapsules from the continuous oil phase into water using a centrifugal method. The suspension of microcapsules were centrifuged for 1 h at 1000 rpm; the oil phase was then decanted off and replaced with heptane, and the system was centrifuged for a further hour. The oil−heptane mixture was then removed and dried under a stream of nitrogen. Once dry, the resulting pellet was resuspended in water by sonication, using Brij 35 as a dispersing aid. Unfortunately, most of the microcapsules were extensively damaged during this procedure. Two, somewhat more successful, alternative procedures were identified. First, the oil-based microcapsule suspension was placed in a separating funnel with a 1 wt % aqueous solution of a cationic surfactant (cetyltrimethylammonium bromide, CTAB) and gently shaken. Overnight the aqueous surfactant solution and oil phase separated. Optical microscopy revealed that microcapsules were now present in the lower aqueous phase, but unfortunately the particle number density was low. A more efficient method was to gently centrifuge (at 400 rpm) a microcapsule suspension placed above a 1 wt % CTAB solution. This method resulted in the transfer of a much greater fraction of the microcapsules, though the transfer of larger capsules was less efficient as they were often damaged. In the absence of surfactant in the aqueous phase, transfer of the microcapsules was unsuccessful, as the capsules collected at the oil/water interface. A variety of different aqueous phase surfactants and concentrations were investigated, with CTAB found to be the most efficient.

Electron micrographs of the microcapsules, dried in air from aqueous CTAB solution, are presented in Figure 4. The flaky material surrounding the capsules is CTAB that has precipitated on drying. The particles are regularly shaped and have sizes between 15 and 30 µm. Numerous different attempts were made to fracture the microcapsules to reveal the shell thickness and structure of the core. However, the low Tg of the polymer hindered these efforts, and no useful images were obtained. A further consequence of the low Tg is that the microcapsules quickly "melted" in the electron beam, producing the structures shown in Figure 4b.

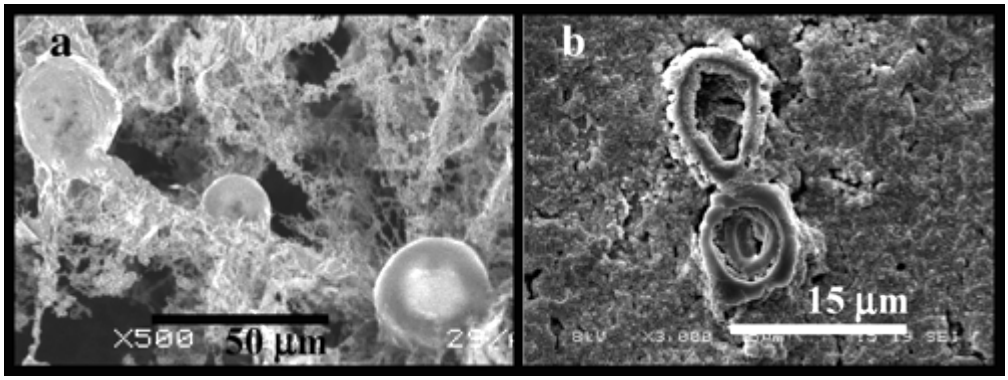


Figure 4 Electron micrographs of PTHF microcapsules. The "flaky" substances in (a) is CTAB that has precipitated during the drying process. (b) Capsule walls that have partially "melted" in the electron beam.

2. PMMA Microcapsules. The difficulties associated with characterizing the PTHF microcapsules are largely due to the low Tg of this polymer. This stimulated efforts to produce aqueous core microcapsules with a polymer having a higher Tg value. PMMA had previously been used by this group to produce capsules with hexadecane cores from an oil/water emulsion;22,24 these microcapsules could be readily characterized using electron microscopy and fracture methods. Provided PMMA could be dissolved in a suitable water/organic solvent mixture, the "inverse" of this earlier oil/water system, i.e., a water/oil emulsion, ought to form the basis of a method for producing aqueous−core microcapsules, with PMMA walls, similar in structure to those produced with PTHF and described in the previous section. A water-miscible cosolvent for PMMA that was not too soluble in any of the potential oil-based continuous phases, and also had a boiling point significantly less than that of water, could not be readily identified.34 However, on the basis of the various solubility parameters34 for (i) the MMA repeating unit (range 8.5−13.3), (ii) water (23.4), and (iii) acetone (9.9), it was found that mixing water and acetone in an approximately 1:20 ratio produced a solvent for PMMA. These three components formed the dispersed "aqueous" phase of the emulsion. Either hexadecane or mineral oil was used for the continuous phase. Acetone is more soluble in hexadecane than in mineral oil. This was a potential disadvantage, although it did increase its rate of removal during the evaporation stage. The ratio of acetone to water required to dissolve the PMMA in the aqueous phase is significantly higher than in the PTHF case.

Figure 5a shows optical micrographs of microcapsules produced, after acetone evaporation, from water/oil emulsions, prepared by dispersing the aqueous phase (water−acetone−PMMA) into the oil phase (mineral oil containing 9 wt % Span 80) under shear (3000 rpm). The spherical particles shown in Figure 5a appear to be aggregated, but these could be readily redispersed with gentle agitation. To confirm that the observed particles were indeed microcapsules, the coverslip was pressed onto the microscope slide in order to rupture the particles. The image in Figure 5b shows a particle where a portion of the capsule has splintered away, and the core liquid appears to be leaking into the bulk. Figure 5c,d shows another broken particle from two different orientations, both of which suggest core−shell type morphology.

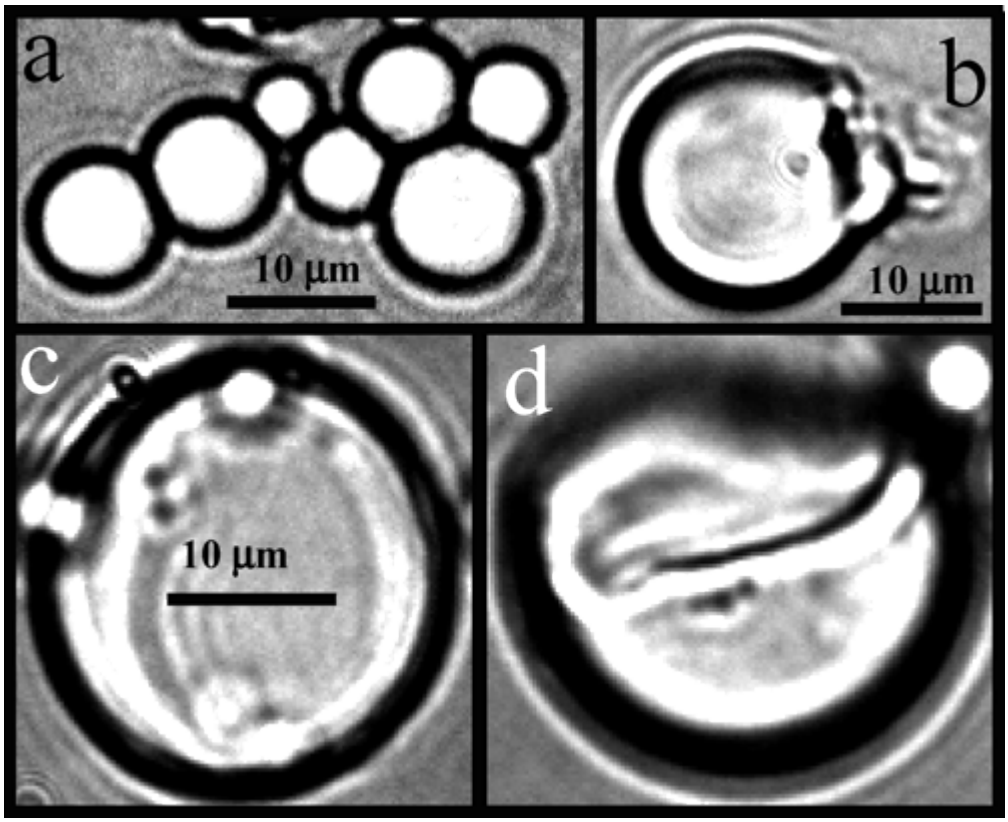


Figure 5 Optical micrographs of PMMA microcapsules: (a) microcapsules aggregated together that could be readily redispersed with gentle agitation; (b) a microcapsule has been ruptured, and the core water appears to leaching into the surrounding oil; (c, d) from different orientations, a microcapsule that has been broken in half, revealing the core structure.

To produce larger microcapsules that could be characterized using light microscopy, the surfactant concentration was reduced to 1 wt % and the shear speed to 1000 rpm. In this case hexadecane was used for the continuous phase. As may be seen in Figure 6a, the microcapsules formed are indeed larger than those shown in Figure 5, but as the parent emulsion was also less stable, it is unclear whether this size increase is due to larger initial emulsion droplets, droplet coalescence during acetone removal, or both. These larger particles have a strikingly different morphology to those presented in Figure 5 in that they are polynuclear rather than a (more or less) single homogeneous

(mononuclear) core. This can be most clearly seen in Figure 6b where the particle has been fractured to reveal better the core structure and also in Figure 7, which shows an electron micrograph of a similar particle.

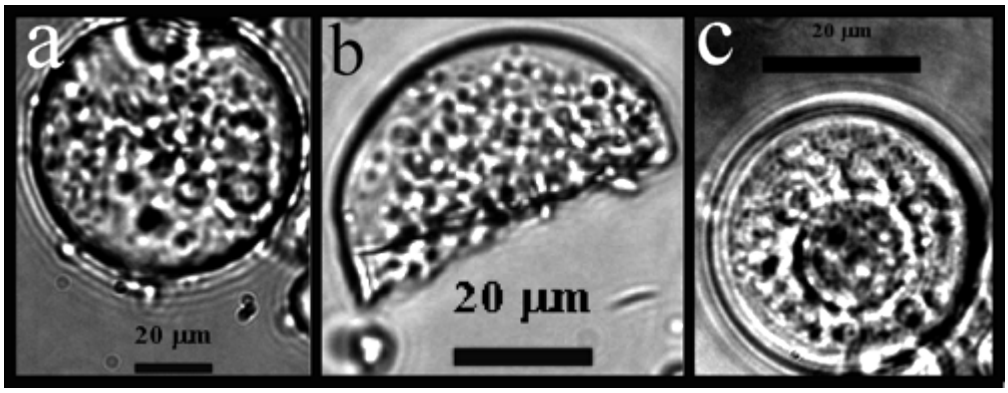


Figure 6 (a) A typical large, multinuclear PMMA microcapsule formed at low surfactant concentrations and low shear. (b) A similar particle that has been fractured. (c) A microcapsule where the rate of acetone removal has been slowed, allowing a larger core to form.

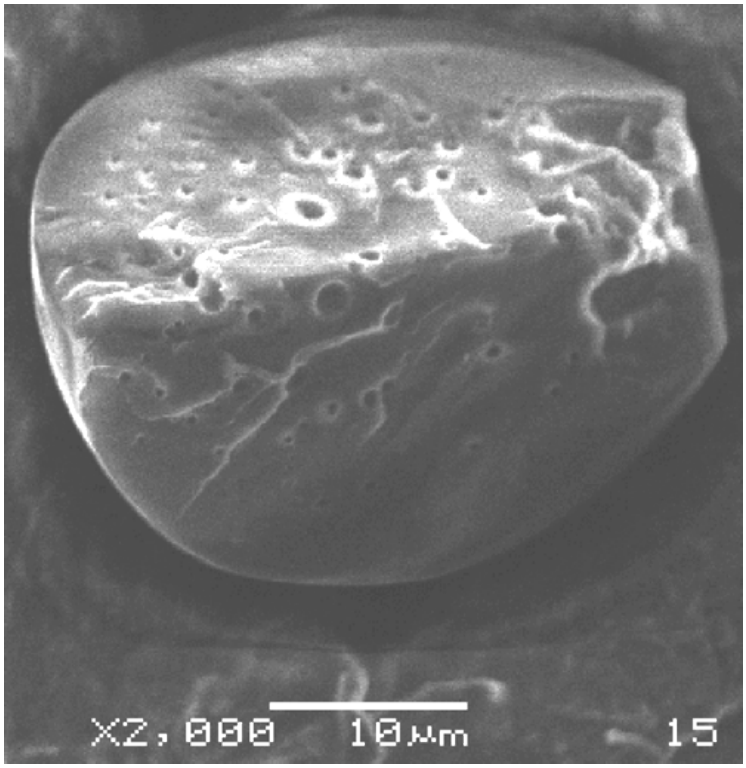


Figure 7 Electron micrograph of a large, polynuclear PMMA microcapsule.

In the previous work with oil-core microcapsules,22 and for the PTHF system described here, the concentration of the volatile, good solvent in the internal phase of the initial emulsion was significantly higher than the minimum required to just dissolve the polymer. However, in the PMMA case the concentration of acetone added to water was just in excess of that required to dissolve the

polymer, so polymer starts to phase separate as soon as the first fraction of acetone evaporates. Also, the final, relative volume of aqueous phase left, after acetone removal will be rather smaller, and the amount of "solvent" solvating the polymer in the precipitated phase will be less. These factors, combined with the fact that PMMA is a more rigid (higher Tg) polymer than PTHF, could mean that the polymer does not readily migrate to the droplet interface. Instead, the polymer forms a continuous matrix, with small water droplets dispersed within this matrix. This would account for the polynuclear morphology seen in Figure 6. A second explanation which could be considered is that, unlike the case of the smaller (mononuclear) microcapsules shown in Figure 5, the initial water/oil emulsion droplets are less stable to coalescence, so the polynuclear structure results from multidroplet coalescence during evaporation of the acetone. This could lead to very small water droplets in a polymer matrix after all the acetone has been removed, i.e., consistent again with the images seen in Figure 6. However, direct observation of the microcapsule formation process, using optical microscopy, indicated that large-scale coalescence was not occurring during evaporation of the acetone (although "peanut"-shaped particles were occasionally seen, which would be a result of partial coalescence). It would seem that the explanation based on the restricted migration of the PMMA to the droplet interface is the more likely one. The principal reason why the smaller microcapsules shown in Figure 5 are essentially mononuclear, compared to the polynuclear ones shown in Figure 6, must have to do with the different oils used as the continuous phase (mineral oil and hexadecane, respectively). As mentioned earlier, acetone is significantly more soluble in hexadecane, and this would lead to much faster removal of the acetone from the droplets, again inhibiting polymer migration. Figure 6c shows a capsule which has been formed at a slower acetone removal rate; there is some, albeit limited, evidence that although still polynuclear, the dispersed units inside the core are somewhat larger.

The more rigid nature of the PMMA microcapsules allowed these particles to be readily transferred into water. The method described earlier for the PTHF microcapsules, whereby the oil-based microcapsule suspension was placed on top of an aqueous surfactant solution and then centrifuged (1000 rpm), was also successful for the PMMA microcapsules. It was found to be easier to do this, however, if the microcapsules were first resuspended in hexane.

3. PIBMA Microcapsules. It was decided to investigate PIBMA as a possible candidate for forming the polymer shell, as this has a Tg value (55 °C) intermediate between that of PMMA (Tg = 105 °C) and PTHF (Tg = −84 °C). It was hoped that, being less "rigid", it might migrate more readily, when solvated, to the droplet interface during acetone evaporation. Various microcapsules formed from an initial water/oil emulsion (aqueous phase: PIBMA + water + acetone; oil phase: mineral oil with 4 wt % Span 80) are shown in Figure 8. The microcapsules formed in this case are also polynuclear, although the particle size of the units dispersed in the polymer matrix do seem larger than in the PMMA case, certainly in Figure 8c (compare Figure 6). The difference between parts a and b of Figure 8 is that, in the latter case, the mass of polymer used was reduced by 25%. Another variation tried was to hold the mass of PIBMA and water constant but to double the mass of acetone in the original water/oil emulsion. The resulting microcapsules, formed after acetone evaporation, are shown in Figure 8c. Although of similar size to the microcapsules shown in Figure 8a,b, they are strikingly different in appearance. There appear to be much larger units dispersed in the polymer matrix in Figure 8c.

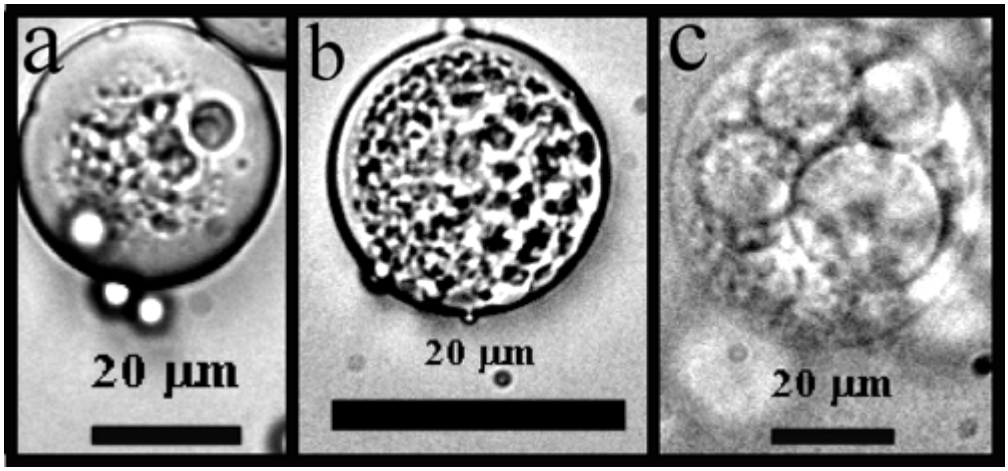


Figure 8 PIBMA microcapsules where the core size has been altered by varying the mass of polymer or good solvent in the emulsion. The conditions that lead to each particle type are provided in the text.

It is difficult to offer a clear explanation at present as to what the exact nature of the polynuclear cores are in the PMMA and PIBMA microcapsules, and how they form. One feature, observed under the optical microscope, with the PIBMA system during the acetone evaporation stage, was some evidence of “acorn” formation and subsequent detachment of the (acetone-rich) aqueous phase from the polymer-rich phase. The formation, in certain cases, of acorn-likes structure which then separate into two separate droplets has been noted previously by Loxley and Vincent in preparing oil-core microcapsules from oil/water emulsions22 and was found to be a consequence of the emulsion stabilizer used. It was concluded that, to obtain microcapsules rather than acorns, the interfacial tensions between the core phase, the polymer (shell) phase, and the continuous phase must be carefully balanced.22,25 In essence, the oil/water interfacial tension must be greater than that of both the polymer/oil interface and the polymer/water interface, so as to minimize the likelihood of any oil/water interface being present in the system. Loxley and Vincent found for their oil-core microcapsules that traditional surfactants reduced the water/oil interfacial tension too much, such that acorns formed. They overcame this problem by using polymeric stabilizers.22 There is an inherent problem, which is difficult to surmount in the reverse case, that is, in trying to form water-core microcapsules. This has to do with the fact that, in this case, the aqueous phase necessarily contains a large percentage of an organic solvent to dissolve the shell-forming polymer. Thus, the initial interfacial tension between the aqueous/acetone phase and the oil phase will always be low (even without a surfactant present) and invariably lower than the polymer/oil and polymer/aqueous phase interfacial tensions (since the polymer should have a low solubility in both final liquid phases). The only reason why water-core microcapsules (mononuclear or polynuclear) do form in many cases is that equilibrium conditions do not apply during the acetone evaporation stage, and the final interfacial tensions in the system, rather than the initial ones, may be more relevant. Indeed, kinetic factors may well dominate over equilibrium ones during microcapsule formation, as the acetone evaporates.

Conclusions

Aqueous core microcapsules with mononuclear and polynuclear morphologies have been formed by phase-separating the polymer from the internal phase of a water/oil emulsion. PTHF has many of the required physical properties for producing water core−shell microcapsules by this route and appears to produce the desired morphology, but its low Tg value makes characterization and transferring the microcapsules produced out of the oil phase into water somewhat more difficult, although methods were developed to achieve this.

PMMA has a much higher Tg value than PTHF but is only soluble in water when high concentrations of acetone are present. Upon acetone evaporation polynuclear capsules are produced, particularly if hexadecane is used as the oil continuous phase. There is a greater chance of producing the more desirable mononuclear cores with mineral oil as the continuous phase; acetone solubility is much less in this oil. It is suggested that the high Tg value (rigidity), and poor solvation of the PMMA chains by water, restricts the migration of the polymer to the droplet interface. Hence, a polymer matrix, with very small water droplets dispersed therein, tends to form rather than a true polymer shell surrounding a (single) water core, particularly if the acetone is removed too rapidly. Transfer of these harder shell microcapsules into a continuous aqueous phase was readily achieved.

PIBMA has an intermediate Tg value, between that of PTHF and PMMA, and should therefore be more mobile than PMMA, particularly in a solvent environment. However, the microcapsules produced with this polymer also had a polynuclear morphology, within a continuous polymer matrix. Some evidence was found for “acorn” formation with this system. This has to do with the incorrect balance of the initial interfacial tensions in the system to give the desired core−shell morphology. However, the reason that even polynuclear microcapsules can be formed with this system is that kinetic factors may win out over equilibrium ones as the acetone evaporates.

As with the oil-core microcapsules produced by Loxley and Vincent,22 the main application of water-core microcapsules would be in controlled release systems. Here the advantage of having water-core (rather than oil-core) microcapsules dispersed in water would be that water-soluble actives (e.g., peptides) could be delivered. The next step in that direction would be to incorporate polymer shells which are either dissolvable or swellable (on applying a suitable “trigger”).

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