8300 *Macromolecules* **2005,** *38,* 8300−8307

Cross-Linked, Monodisperse, Micron-Sized Polystyrene Particles by Two-Stage Dispersion Polymerization

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Received May 12, 2005; Revised Manuscript Received July 16, 2005

ABSTRACT: It is well-known that cross-linking agents such as divinylbenzene (DVB) interfere with the dispersion polymerization of styrene in ethanol, a reaction carried out in the presence of polymeric stabilizers such as poly(vinylpyrrolidone). Small amounts of DVB broaden the particle size distribution and lead to irregular particles, whereas modest amounts lead to coagulation. We report that many of these problems can be avoided if one delays the addition of the cross-linking agent until after the end of the nucleation stage of the reaction (e.g., at less than 5% monomer conversion). In this way one can obtain monodisperse polystyrene particles containing 1 wt % ethylene glycol dimethacrylate (EGDMA) as a cross-linker. A second set of problems arises if the cross-linking agent is consumed too early in the reaction, presumably because early network formation limits the swellability of the growing particles. These problems can be overcome by feeding DVB into the reaction over 12 h or by adding EGDMA in successive batches over 6 h. In this way, monodisperse particles with micrometer diameters, and a coefficient of variation of 2% or less, can be obtained containing up to 6 wt % cross-linker based on styrene.

Introduction

Monodisperse polymeric beads in the micrometer-size range have been used as separation media, ion-exchangers, support materials, toners, coatings, calibration standards, and functional beads for medical diagnostics. Micron-sized uniform particles can be made by the successive seeded emulsion polymerization developed by Vanderhoff[1] or the activated swelling and suspension polymerization methods developed by Ugelstad.[2] These are the most frequently quoted procedures, although some other approaches are also available.[3,4] However, all of the above processes for making micrometer diameter polymer particles are complex and difficult to implement on a large scale. Horák[5] has reviewed the various methods that have been developed in recent years to produce uniform polymer particles with diameters larger than 1 μm.

The invention of dispersion polymerization process has greatly facilitated the preparation of monodisperse beads with micrometer diameters, making it a very attractive procedure for a large-scale preparation of such particles. This method, originally developed in the late 1960s,[6−8] saw an explosive growth in interest in the early 1990s, stimulated by the work of Lok and Ober[9] on dispersion polymerization in alcohol using a water-soluble polymer, such as poly(vinylpyrrolidone) (PVP), as the stabilizer. This methodology is most suited to the preparation of beads in the diameter range of 1−15 μm.[10,11] Unfortunately, this approach has still fallen short of its initial promise, as scientists have encountered problems with these reactions when functional comonomers were employed.[12,13] These problems include loss of control of particle size, broadening of the size distribution, odd-shaped particles, and, in the extreme, coagulation of the polymer produced in the reaction.

Some research groups have employed seeded dispersion polymerization[14] in an attempt to overcome these problems. In this approach, one prepares particles by dispersion polymerization and then introduces these particles (often after purification) into a second reaction. The El-Aasser group[15] has used this approach to prepare structured particles by employing a different monomer in the second step. Okubo and co-workers were able to introduce chloromethyl groups[16,17] and vinyl groups[18,19] into the shell of particles produced in this way. In contrast to traditional seeded emulsion polymerization, where the seed latex comprises a very small fraction (2−10%) of the final particle mass, in seeded dispersion polymerization, the polymer formed in the second step represents typically half of the particle mass.

One of the biggest challenges for dispersion polymerization is the synthesis of cross-linked particles. There are many citations in the literature to attest to the fact that dispersion polymerization failed when cross-linking agents are present. One often finds flocculation or coagulation of the product. When the reaction appears to succeed, one finds odd-shaped particles, a broad size distribution, and a lack of control over the reaction. The first report of the consequences of a cross-linking agent on a dispersion polymerization reaction is found in the publication by Tseng et al.[13] They described experiments in which small amounts of divinylbenzene (DVB) were mixed with styrene for dispersion polymerization in ethanol. When the amount of DVB was 0.3 wt % based on the total monomer, the particle size changed and the size distribution was broadened significantly. Further increases in DVB concentration resulted in coagulation of the dispersion.

In a patent, Longley et al.[20] disclose a process for producing cross-linked "monodisperse" polyvinyl polymeric particles of about 1−6 μm size, using isopropyl alcohol or isobutyl alcohol as solvents and by multiaddition of the cross-linking polyvinyl monomer about 0.5−3.0 wt % (based on the total monomer) over the course of the polymerization reaction. They provide little data to support these claims. We note that these solvents have greater solvency for the particle-forming particle produced in the reaction. More recently, Choi

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10.1021/ma050992z CCC: \$30.25

et al.[21] studied the effect of solvency on the size and size distribution of polystyrene particles prepared in the presence of DVB. They were able to prepare cross-linked particles with diameters in the 3−9 μm range in an isopropyl alcohol/toluene mixed-dispersion medium with PVP as a steric stabilizer with a relatively marrow size distribution.

A much more detailed investigation of the synthesis of cross-linked polystyrene particles by dispersion polymerization in ethanol media is described by Thompson et al.[22] When a very small amount (0.02 wt %, based on total monomer) of DVB was present in the initial charge, particles with a very narrow size distribution were obtained. Larger amounts of DVB could be incorporated only if incremental amounts of DVB were added many hours (e.g., 7 h) after the start of the polymerization. In this way they obtained particles with a narrow size distribution containing up to 1 wt % DVB, but the particles were not spherical. These authors pointed out that commercial DVB is normally a mixture of *para* and *meta* isomers. For the para isomer in particular, the first double bond reacts faster than the second and also reacts more rapidly than styrene itself. The preferential consumption of *p*-DVB early in the reaction can be a complicating feature of the use of DVB as a cross-linking agent.

A Czech group has investigated dispersion polymerization as a means of preparing poly(2-hydroxyethyl methacrylate) (PHEMA) particles with micrometer diameters for biomedical applications.[23] The particles obtained have a relatively narrow size distribution that is broader than that obtained for particles prepared by dispersion polymerization of styrene in ethanol. The need for cross-linked particles prompted a detailed investigation reaction conditions that led to incorporation of ethylene glycol dimethacrylate (EGDMA) as a cross-linking agent. They found that delaying addition of the EGDMA until the reaction had run for 2 h led to optimal reaction with minimal perturbation of the particle size distribution.[24] Both papers provide detailed information on the influence of solvent composition on the particles produced in the reaction.

To maintain solvent swellability during the reaction, Kim et al.[25] employed diacrylates formed from oligomeric diols as cross-linking agents for dispersion polymerization. They succeeded in producing PS particles incorporating up to 5 wt % of the cross-linking agent, but it is worth noting that the mole fraction is rather small for a few weight percent of a reactant with a molar mass 1600−3000.

Reaction mixtures containing higher concentrations of cross-linker are less susceptible to the problems described above. For example, in the dispersion polymerization of styrene−DVB mixtures, Hottori et al.[26] found that DVB concentrations up to 0.55 wt % produced stable particles with sizes ranging from 1 to 7 μm, whereas when 2 to 11% DVB was used, coagulation of the dispersion resulted. With 22 wt % DVB, spherical particles were obtained, but these flocculated. Further increases in the DVB concentration resulted in the formation of stable dispersions with sizes ranging from 0.4 to 1.2 μm. Related to these reactions is the precipitation polymerization procedure of Li and Stöver,[27,28] in which the free-radical polymerization of DVB-55 in acetonitrile with gentle agitation, but without added stabilizer, provides spherical polymer particles with a narrow size distribution. DVB-55 is a commercial mixture of 55% *m*- and *p*-DVB + 45% *m*- and *p*-ethylvinylbenzene. This reaction is successful only in marginal solvents in which the polymer precipitates but at low cross-link density remains swollen by the medium. Mechanistic studies[29] indicate that aggregation and cross-linking of soluble oligomers produces solvent-swollen microgels that subsequently desolvate to form particle nuclei. These particles grow by capturing oligomeric radicals in the solution but remain covered by a solvent-swollen gellike layer that provides steric stabilization during the reaction.

We recently discovered,[30] in the dispersion polymerization of styrene in ethanol, that if one delays the addition of a cross-linking agent until the end of the nucleation stage, cross-linked particles of narrow size distribution could be obtained. Since the nucleation stage is complete at very low (a few percent) conversion of monomer, a cross-linking agent such as ethylene glycol dimethacrylate (EGDMA) could be added along with a second charge of monomer and additional solvent, when less than 5% of the monomer had reacted. The particles produced in the reaction had the same particle diameter and the narrow size distribution as in the reaction run in the absence of cross-linker. We referred to this strategy of delaying the addition of the problematic reagent as “two-stage” dispersion polymerization. This strategy allows one to overcome many problems common to dispersion polymerization if the problematic reagent is present at the start of the reaction.

The situation with DVB was more complex, and amounts of cross-linker above 1−2 wt % had a deleterious effect on the reaction. Here we describe experiments that explore these phenomena. We report reaction conditions that allow one to incorporate up to 3 wt % DVB or up to 6 wt % EGDMA in the synthesis of polystyrene microspheres with a narrow size distribution. These experiments provide insights into the problems caused by the presence of cross-linking agents in the reaction, even if they are added after the end of the nucleation stage.

Experimental Section

Reagents. All organic reagents were used without further purification, including styrene (Aldrich), divinylbenzene (DVB, 80%, mixture of isomers, Aldrich), ethylene glycol dimethacrylate (EGDMA, Aldrich), methanol and ethanol, poly(vinylpyrrolidone) (PVP, M_w = 55 000 g/mol, Aldrich), Triton X-305 (70% solution in water, Aldrich), Triton N-20 (TCI), 2,2′-azobis(isobutyronitrile) (AIBN, Aldrich), and 2,2′-azobis(2-methylbutyronitrile) (AMBN, Wako Pure Chemical Industries Ltd.).

One-Stage Dispersion Polymerization. The recipes for the one-stage dispersion copolymerization of styrene with DVB in ethanol are listed in Table 1. To a three-neck 150 mL round-bottom flask equipped with a condenser and a gas inlet, DVB (0.042 g, 0.35 wt % based on styrene) was dissolved in ethanol (79 g). PVP (4.0 g), Triton N-20 (0.72 g), and styrene (4.0 g) were added to the flask, and then the flask was placed in an oil bath. In the homopolymerization reaction, no cross-linking agent was added. The solution was deoxygenated by bubbling nitrogen, heated to the reaction temperature 80 °C, and stirred mechanically at 100 rpm. When the reaction mixture reached the reaction temperature, a solution of AIBN (0.6 g) dissolved in styrene was deoxygenated and added to the reaction flask. The monomer conversion was monitored gravimetrically by removing aliquots during the polymerization.

Two-Stage Batch Dispersion Polymerization. The standard recipe for the two-stage dispersion copolymerization of styrene and DVB, or styrene and EGDMA, in ethanol is listed in Table 2. The following procedure was used: all of the

Table 1. Recipes for the One-Stage Dispersion Copolymerization of Styrene in Ethanol (Amounts in grams)

run	L0	L1	L2	L3	S0
styrene	12.0	12.0	4.2	4.4	6.25
EtOH	79.0	79.0	26.1	27.7	18.75
PVP	4.0	4.0	1.0	1.06	1.0
Triton N-20[b,c]	0.72	0.72	0.33	0.35	0.35 (Triton X-305)[b,c]
DVB	0	0.35[a]	0.67[a]	1.0[a]	0
AIBN	0.6	0.6	0.134	0.14	0.25 (AMBN)
polymerization temp (°C)	80	80	80	80	70

[a] Wt % based on styrene. [b] These two surfactants have similar properties. While we have not run comparative tests between them, we believe they act similarly. In both run L0 and S0 (no DVB), monodisperse particles were obtained. [c] Some research groups have argued that the use of a nonionic surfactant as a costabilizer is not necessary for the dispersion polymerization of styrene in alcohol.[14] We have not investigated this point.

Table 2. Standard Recipe for the Two-Stage Dispersion Copolymerization of Styrene and DVB or EGDMA in Ethanol

		amount (g)	
	materials	1st stage	2nd stage
monomer	styrene	6.25	6.25
cross-linker	DVB or EGDMA	0	0.125
medium	ethanol	18.75	18.75
stabilizer	PVP	1.0	
costabilizer	Triton X-305	0.35	
initiator	AMBN	0.25	

stabilizer (PVP), the costabilizer (Triton X-305), and initiator (AMBN) and half of the monomer and ethanol were added to a 250 mL three-neck reaction flask equipped with a condenser and a gas inlet. After a homogeneous solution formed at room temperature, the solution was deoxygenated by bubbling nitrogen gas at room temperature for at least 30 min. Then the flask was placed in a 70 °C oil bath and stirred mechanically at 100 rpm. The DVB (or EGDMA) was dissolved in the remaining styrene plus ethanol at 70 °C under nitrogen. After the DVB had dissolved and the polymerization reaction had run for 1 h, the hot DVB (or EGDMA) solution was added into the reaction flask. The monomer conversion was determined gravimetrically by removing aliquots during the polymerization.

Two-Stage Multibatch Dispersion Polymerization. The recipe and procedure were the same as that described above, except that after the hot EGDMA (1 wt % based on total styrene) solution was added ca. 1 h after the first stage of the reaction had begun, a second aliquot of EGDMA (0.625 g, 5 wt % based on total styrene) dissolved in ethanol (5.0 g) and was added to the reaction 6 h later.

Two-Stage Semicontinuous Dispersion Polymerization. The recipe and procedure were the same as that described above, except that the DVB/ethanol solution was added slowly over 12 h starting ca. 1 h after the first stage of the reaction had begun.

Determination of Gel Content. For particles synthesized in the presence of less than 0.5 wt % cross-linker, we were able to separate a sol and gel fraction of the polymer. For particles prepared in the presence of higher quantities of cross-linking agent, it was very difficult to isolate a sol component. We assume that all polymer formed after introduction of the cross-linking agent is in the gel state. For the sample prepared in the presence of 0.35 wt % DVB, the final polymer particles were purified with ethanol by a three-time centrifugation–redispersion process to remove the free and physically absorbed PVP. Then the purified particles were dried to a constant weight W_0. The dried polymer was subsequently immersed in $CHCl_3$. The mixture was agitated gently at room temperature for 24 h. The resulting solution was then centrifuged at 20 000 rpm for 20 min, and the top transparent layer was poured off and saved. The precipitate was washed three more times with excess $CHCl_3$ to remove residual sols from the gel. All the $CHCl_3$ solutions were combined and dried for GPC analysis. The remaining sample (the gel fraction) was dried and weighed (W_1). The gel content (%) was calculated from the expression

$$\text{gel content (\%)} = (W_1/W_0) \times 100$$

Particle Characterization. The particle size and size distribution were examined both by optical microscopy (Olympus, X41) and scanning electron microscopy (S-5200 SEM, Hitachi). To prepare samples for optical microscopy, the final polymer particle suspension was diluted with water, and a drop was placed on a clean glass microscope slide. The SEM samples were prepared with a drop of diluted suspension on a mica film. The molecular weight and molecular weight distribution were determined by gel permeation chromatography (GPC) in tetrahydrofuran (THF) using polystyrene calibration standards. The particle size distributions were determined by SEM. A particle size histogram was constructed from measurements of 200–300 individual particles from the electron micrographs.

Results and Discussion

Lok and Ober[9] established that the dispersion polymerization of styrene in ethanol in the presence of poly(vinylpyrrolidone) (PVP) as a stabilizer produces beautiful particles with micrometer dimensions and a very narrow size distribution. In this reaction, one can manipulate particle size by varying the polarity of the solvent or the amount of PVP in the recipe. One of the limitations of the reaction is that the nucleation stage is extremely sensitive to small variations in reaction conditions.[22] For example, comonomers that can be employed without problems in traditional emulsion polymerization, such as functional monomers,[12] fluorescent dye derivatives, and cross-linking agents, interfere seriously with the dispersion polymerization reaction. If these species are present at the start of the reaction, even in only tiny amounts, problems arise. The particle size and shape change, the size distribution broadens, and/or the system loses colloidal stability. We refer to these species as problematic reagents, and we refer to batch reactions in which all the reagents are present at the start of the reaction as a one-stage reaction. To place our results on the effects of cross-linking agents in context, we begin by describing the one-stage reaction of styrene plus PVP in ethanol in the presence of a tiny amount of DVB, along the lines initially reported by Tseng et al.[13]

Cross-Linked PS Particles by the One-Stage Method. We carried out one-stage dispersion copolymerization reactions of styrene in the presence of three concentrations of DVB (0.35, 0.67, and 1 wt % of DVB based on styrene). The recipes are presented in Table 1. For the reactions with 0.35 and 0.67 wt % DVB, the reaction mixtures became cloudy in a few minutes and "milky" in less than 10 min. With a higher DVB content (1 wt %), flocculation occurred after only 5 min, and the amount of aggregates increased during the polymerization. SEM pictures of the cross-linked particles,

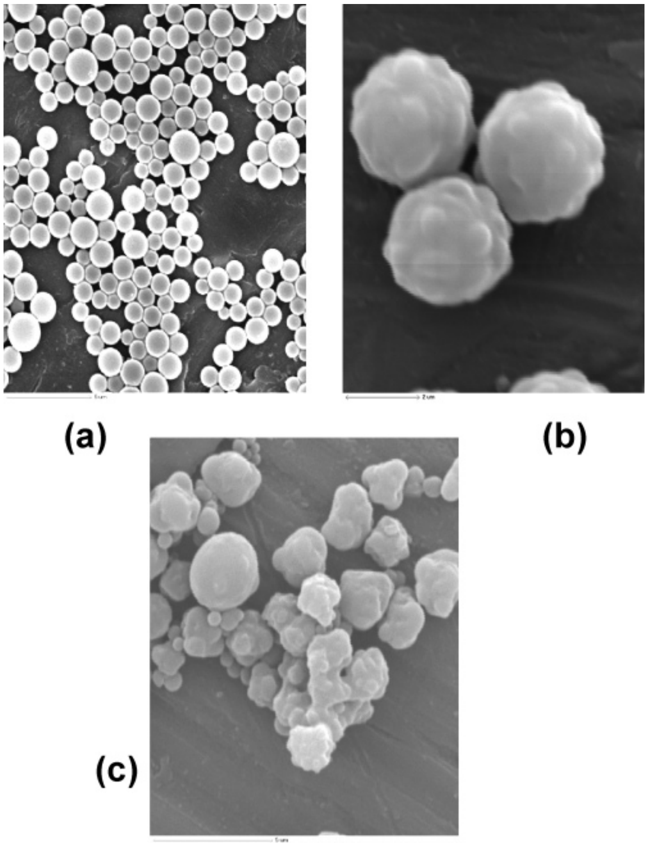


Figure 1. SEM images of cross-linked PS particles prepared by conventional dispersion polymerization with different amounts of DVB (based on styrene). The numbers following the DVB content are estimates of the mean particle diameter. (a) 0.35 wt %, polydisperse, 0.6−2 μm. (b) 0.67 wt %, nonspherical, ca. 3 μm. (c) 1 wt %, 80% flocculation, irregular shapes of dispersed particles.

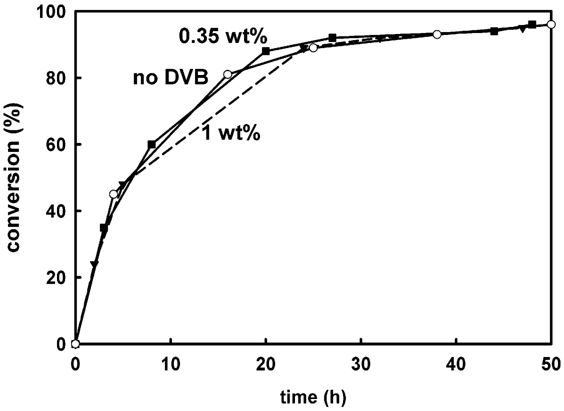


Figure 2. Plots of styrene conversion vs time for the conventional dispersion polymerization of styrene carried out with different amounts of DVB (based on the styrene). (■) 0.35 wt %, (▼) 1 wt %, and (○) no DVB.

prepared using the recipes in Table 1, are presented in Figure 1. With 0.35 wt % of DVB, the PS particles are polydisperse (Figure 1a), and with 0.67 wt % of DVB, the particles are no longer spherical (Figure 1b). Figure 1c corresponds to the dispersed part (20 wt % of the total polymer) obtained with 1 wt % of DVB, and one notices that the particles have irregular shapes. These results are similar to those originally reported by Tseng et al.[13]

The monomer conversion rates for these reactions are plotted in Figure 2. One sees that the presence of DVB in the monomer mixture has no influence on the polymerization rate of styrene. The final product obtained with 0.35 wt % of DVB in the feed is a homogeneous dispersion of polydisperse PS particles in ethanol. These particles are not fully cross-linked since the gel content measured in $CHCl_3$ or DMF is only 30%. We separated the sol and gel fractions of this sample. By GPC, we determined $M_w = 94\ 000$ and $M_w/M_n = 1.5$ for the soluble fraction of this polymer.

DVB Cross-Linked PS Particles by the Two-Stage Batch Method. To avoid the influence of DVB on the nucleation stage, we delayed the addition of DVB until 1 h after the start of the reaction. We added 1 wt % DVB (based on total styrene) as part of a styrene/ethanol mixture to the seed particles formed during the first hour of the reaction. At early stages of the subsequent monomer conversion, the size distribution remained uniform. But 1.5 h later, most particles coagulated over a short period time, and the remaining solution was clear (Table 3, S-2).

In the two-stage methodology, addition of the DVB is delayed until the nucleation stage is complete. As consequence, problems caused by DVB in the reaction cannot be due to its interference with particle nucleation. It is more likely to be related to the rapid consumption of the DVB. This could lead to rapid formation of a cross-linked network that could affect the ability of the growing particles to be swollen by monomer. As mentioned in the Introduction, *p*-DVB is significantly more reactive than styrene; *m*-DVB is slightly more reactive ($r_{st}/r_{p-DVB} = 0.15/1.00$ for St/*p*-DVB and $r_{st}/r_{m-DVB} = 0.6/0.88$ for St/*m*-DVB copolymerization at 80 °C using benzoyl peroxide as initiator).[31] The result of this copolymerization of styrene with DVB is a tendency toward the congregation of *p*-DVB units in the PS chains and a more even distribution of *m*-DVB isomers.[32] After one double bond of DVB is reacted, the pendant vinyl group is less reactive than either monomer. For example, in the copolymerization of styrene with pure *p*-DVB and *m*-DVB, Hild and Rempp[32] observed that the onset of gelation occurred much earlier and at lower conversion in the *p*-DVB system, strongly suggesting that such pendant groups in the *p*-DVB are more reactive than their *meta*-substituted equivalents. These results point to early gelation as the source of the difficulty in the dispersion polymerization reaction.

DVB Cross-Linked Monodisperse PS Particles by Two-Stage Semicontinuous Addition. To avoid rapid consumption of DVB, we carried out experiments in which the DVB solution was added continuously over 12 h, beginning 1.5 h after the reaction had begun. In this way, particles containing up to 3 wt % DVB (see Figure 3) could be obtained without a significant change in the narrow particle size distribution. The difference between this reaction and the two-stage batch reaction is the timing of the formation of cross-links. In the batch process, the cross-link density of the polymer at low conversion is much higher, and the cross-link density of the polymer at high conversion is lower, than that for the semicontinuous process. Even though the total DVB incorporated into the polymers in the two reactions was the same, and the average cross-link density was the same, the stability of the particles during the copolymerization reaction was totally different. Much more DVB could be incorporated into the polymer particles when it was added slowly to the reaction than in the batch reaction. We infer from this result that the

Table 3. Effect of Comonomer on the Particle Size and Size Distribution

sample	comonomer	content, wt %	D, μm	CV,[a] %	method	remark
L-1	DVB	0.35	0.6−2		one-stage	polydisperse
L-2	DVB	0.67	∼3		one-stage	nonspherical
L-3	DVB	1			one-stage	coagulum after 5 min
S-0	none		2.0	<1	one-stage	monodisperse
S-1	none		3.2	<1	two-stage	monodisperse
S-2	DVB	1			two-stage batch	coagulum after 120 min
S-3[b]	DVB	1	2.7	2.5	two-stage semicontinuous	monodisperse
S-4	DVB	3	2.3	3.2	two-stage semicontinuous	monodisperse
S-5	EGDMA	1	2.6	2.0	two-stage batch	monodisperse
S-6	EGDMA	2			two-stage batch	coagulum after 200 min
S-7	EGDMA	6	3.4	<1	two-stage multibatch	monodisperse

[a] CV = $(1/n)\sum_{i=1}^{n}|(D_i - D_{\mathrm{av}})|/D_{\mathrm{av}}$, where D_{av} is the average diameter of all particles. [b] Note: AMBN dissolved in styrene and added after the system was heated to 70 °C.

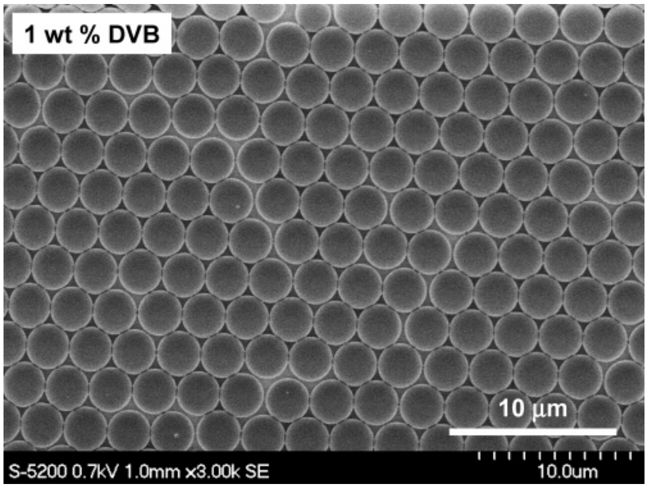


Figure 3. SEM image of DVB-cross-linked PS particles (1 wt % of DVB based on the total styrene added) synthesized by the two-stage semibatch method. The marker bar = 10 μm.

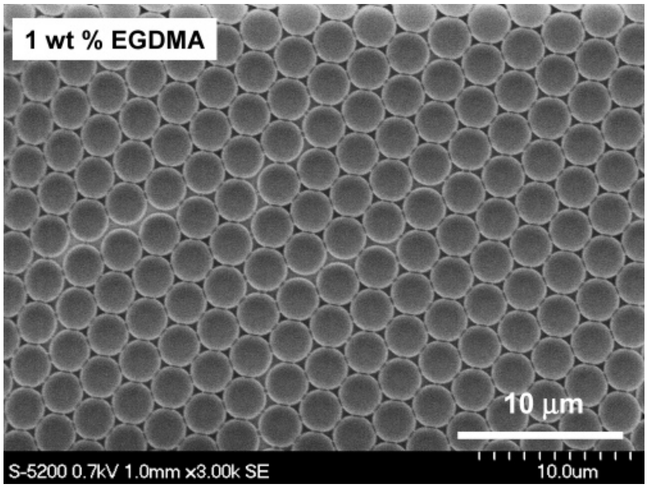


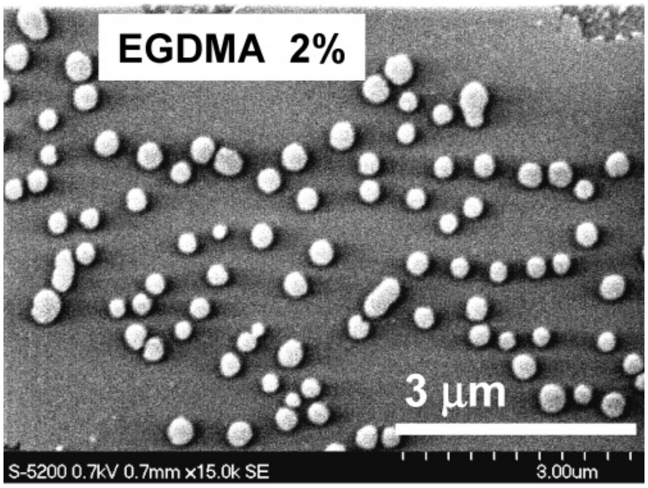
Figure 4. SEM image of EGDMA-cross-linked PS particles (1 wt % of EGDMA based on the total styrene added) synthesized by the two-stage batch method. The marker bar = 10 μm.

swellability of the seed particles by monomers at low conversion and of the growing particles at moderate conversion (60%) is crucial for a dispersion polymerization reaction to produce stable particles.

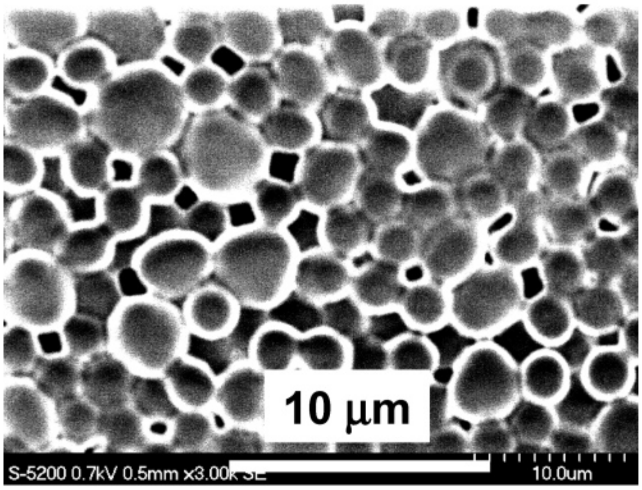
In many dispersion polymerization reactions, some soluble polymer is produced in addition to particles. We have detected traces of an ethanol-soluble oligomer by GPC in our syntheses of non-cross-linked particles. The presence of significant amounts of this type of polymer will show up in SEM images of the particles making the images less sharp. This oligomer can be removed by centrifuging the particles and then resuspending them in ethanol. The images in Figure 3 and those shown below are taken of particles directly from the reaction mixture.

EGDMA Cross-Linked Monodisperse PS Particles by the Two-Stage Batch Method. EGDMA has a more favorable reactivity ratio for reaction with styrene than *p*-DVB ($r_{\mathrm{st}} = 0.40$ and $r_{\mathrm{EGDMA}} = 0.64$ for St/EGDMA copolymerization[33]), and the reactivities of the two methacrylate groups of EGDMA are essentially identical. As a consequence, one expects that many of the problems encountered when DVB is used as a cross-linker will be less serious for EGDMA. Here we examine EGDMA as a cross-linking agent for the dispersion polymerization of styrene. We mixed the EGDMA with half of the styrene and half of the ethanol. This portion was added to the polymerization 1.5 h after initiation of the reaction of the initial charge of styrene. We found that when the amount of EGDMA added was 1 wt % based on total styrene, the final particles possessed the same particle size and the same size distribution as un-cross-linked particles prepared in the same way but without adding EGDMA in the second stage. This result indicates that the number of particles was determined in the nucleation stage and that the cross-linker, EGDMA, added after the nucleation stage did not affect the particle size and size distribution. An SEM image of these cross-linked PS particles is shown in Figure 4. Monodisperse cross-linked particles were obtained.

To investigate the effect of the cross-linking density on the stability of growing particles, we carried out a series of reactions in which increased amounts of EGDMA were added during the particle growth stage. When 2 wt % EGDMA (based on total styrene) was added along with styrene and ethanol in the two-stage batch method, the growing cross-linked particles gradually lost stability. A sample taken from the reaction 1 h after the EGDMA was added showed that particles began to aggregate into odd-shaped larger particles, but the dispersion itself was stable. In Figure 5a, we present an SEM image of particles formed 85 min after the EGDMA was added to this reaction. At 205 min after EGDMA was added, most of the original particles were aggregated (Figure 5b). After 24 h, about 70% of the PS particles were aggregated but in the form of loose large grains, ranging in size from 1 to 5 mm. The particles that remained colloidally dispersed at this time were most likely produced by secondary nucleation after most of the original particles had aggregated. These results show that if the EGDMA cross-linker was added in a batch mode, the amount of cross-linker that could



t_1 = 85 min



t_1 = 205 min

Figure 5. SEM images of EGDMA-cross-linked PS particles (2 wt % of EGDMA based on the total styrene added) synthesized by the two-stage batch method (Samples were taken from the reaction 85 and 205 min after the EGDMA was added.)

be incorporated, while maintaining a narrow size distribution, is limited (for EGDMA < 2 wt %).

To try to overcome problems encountered with the batch addition of EGDMA in the second stage of the dispersion polymerization, we added the EGDMA in two batches. In one reaction we added 1 wt % of EGDMA (based on total styrene) in styrene/ethanol 1.5 h after initiation of the reaction, and an additional 5 wt % EGDMA in ethanol was added 6 h later. From the data in Figure 2, we infer that the reaction, when the second aliquot of EGDMA was added, had consumed about 60−70% of the styrene monomer. Monodisperse highly cross-linked particles were obtained by this postnucleation multiaddition method. An SEM image of the resulting particles is shown in Figure 6. While the particles maintain their very narrow size distribution, one can see in the image a variability in surface morphology. Some, but not all, of the particles have tiny rough features on the surface that may arise from capture of tiny cross-linked nuclei generated in late stages of the reaction.

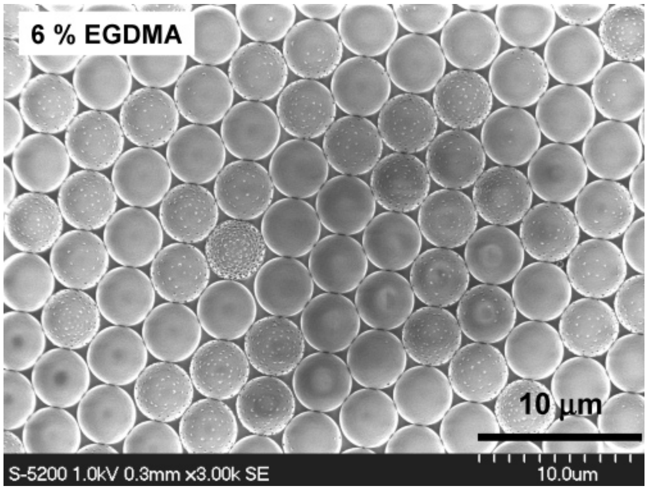


Figure 6. SEM image of EGDMA-cross-linked PS particles (6 wt % of EGDMA based on the total styrene added) by the two-stage batch multiaddition method (1 wt % of EGDMA in styrene/ethanol was added 1.5 h after initiation of the reaction, and an additional 5 wt % of EGDMA in ethanol was added 6 h later). The marker bar = 10 μm.

Particle Growth Mechanism of Dispersion Copolymerization of Styrene and Cross-Linker. In studies of surfactant-free emulsion copolymerizations of styrene and DVB, the Salovey group was able to include up to 10 wt % of DVB by batch[34] and semicontinuous[35] processes, both of which yielded monodisperse distributions of smooth-surfaced, spherical particles with diameters less than 1 μm. The main differences between (seeded) dispersion polymerization and seeded emulsion polymerization are that the partitioning of monomer and the polymerization loci are different. For seeded emulsion polymerization, the monomer concentration in the water phase is very low. Radicals form in the water phase and diffuse into growing seed particles. Some polymer is initiated in the water phase, but because the critical molecular weight of PS in water is so low, these growing chains are captured immediately by the seed particles. The monomers diffuse from monomer droplets to growing seed particles, and the seed particles are the main loci for polymerization. Therefore, the polymerization in the water phase is negligible.

In the Ugelstad seeded suspension polymerization, seed particles are swollen with monomers and then polymerized. To increase the swellability of the seed particles, oligomer seed particles are used, and an osmotic swelling agent is first absorbed into the seed particles.[2] Cross-linked PS particles are not suitable as seed particles due to their very limited swellability. After all the cross-linker and styrene are absorbed into the seed particles, these swollen particles are polymerized to form cross-linked particles. Water-soluble inhibitor is added to prevent polymerization in the water phase. Oil-soluble initiators are used to reduce the tendency to form new particles in the aqueous phase. Every swollen particle acts like a bulk reactor, and all the polymerization occurs in the particle phase.

For dispersion polymerization, the monomer and initiator concentrations in ethanol are high, so that the alcohol phase is always a major locus of polymerization in addition to the particle phase. The critical molecular weight of PS (corresponding to the chain length of PS that precipitates at the reaction temperature) is much higher for dispersion polymerization in ethanol than that for emulsion polymerization in water. The PS molecules above the critical molecular weight will precipitate onto preexisting particles. In addition, new unstable nuclei form in the continuous phase and precipitate onto existing particles. During the particle growth stage, dispersion polymerization can be considered to be a seeded polymerization reaction. The morphology and stability of the final particles are determined by the amount of cross-linker present in the system. From our experiments at low cross-linker level (e.g., 1.5 wt % for EGDMA), monodisperse spherical particles were obtained. At this moderate EGDMA level, coagulation of the dispersion resulted. Thus, even if problems with particle nucleation are avoided, too much network formation early in the reaction interferes with particle growth.

For dispersion polymerization of styrene without cross-linker or with low cross-linker level (for DVB or EGDMA batch process, less than 1.5 wt %), the growing particles during polymerization are swollen by monomer. We imagine that the oligoradicals or dead polymer formed in solution that precipitate on the particle surface can dissolve in and diffuse into the growing particles. The particle surface is not affected significantly during polymerization. As a consequence, the growing particles remain spherical and stable during polymerization. For dispersion polymerization of styrene at a more elevated cross-linker level, the seed particles are moderately cross-linked and have limited swellability. Here we imagine that oligoradicals or the dead polymer that deposits on the surface of growing particles has difficulty diffusing into the interior of these particles. They can form patches on the surface of these particles that can grow into nodules. These nodules can swell and grow to promote the formation of odd-shaped particles. Because there is not enough grafted stabilizer on the surface of the nodules, these areas may be sources of colloidal instability.

As mentioned in the Introduction, the El-Aasser group[14] reported successful dispersion polymerization reactions at high (>22 wt %) levels of DVB. These results can be explained through a mechanism in which the growing particles are cross-linked with very limited swellability, and the polymer precipitated from solution is also sufficiently cross-linked that it is not easily swollen by monomer. The ethanol phase becomes the major locus of polymerization. Thus, precipitation onto the nucleated particles is the primary mechanism of particle growth.[26] This differs from previous models for dispersion polymerization of styrene in ethanol in that growth in these systems is thought to occur primarily by polymerization within the particles.[36] At high cross-linker concentration, the reaction mechanism changes to one that more resembles the precipitation polymerization of DVB itself as described by Li and Stöver.[27,28]

Summary

The dispersion polymerization process can be separated into two stages, a “nucleation stage” and a “particle growth stage”. The nucleation stage is short but very complex and sensitive, while the particle growth stage is long and relatively robust. Dispersion polymerization can be considered as a seeded polymerization, in which the seed particles are formed in situ during the nucleation stage. Throughout the particle growth stage, until late in the reaction, the growing particles remain swollen by monomer. The particle number and particle size distribution are determined only by the nucleation stage if there is no coalescence or secondary nucleation during the particle growth stage.

Cross-linking agents affect particle growth in two ways. First, if they are present at the beginning of the reaction, they interfere with the sensitive particle nucleation step. One of our contributions to the synthesis of cross-linked polymeric microspheres is the discovery that if the cross-linking agent is added to the reaction at low conversion (e.g., 5%), but after completion of the nucleation stage, this problem can be avoided. Second, network formation limits the swellability of the growing particles. In the case of *p*-DVB, present in the commercial DVB sample, rapid consumption of this species leads to enrichment of cross-linking sites within the growing particles. The reaction fails if the DVB is added in a batch mode. Slow continuous addition of DVB, up to about 3 wt %, allows one to obtain spherical cross-linked particles with a narrow size distribution. With EGDMA, which has a more favorable reactivity ratio for reaction with styrene, up to about 1.5 wt % can be added in the batch mode once the nucleation stage of the reaction is over. Larger amounts promote particle coagulation.

To obtain particles containing a high degree of cross-linking, one can add a small amount (e.g., 1 wt %) of EGDMA at low conversion and incrementally larger amounts at higher conversion. We were able to obtain spherical particles with a very narrow size distribution when an additional 5 wt % EGDMA was added along with ethanol 6 h after the first EGDMA solution was added. It is important to emphasize that these particles are unlikely to have a uniform cross-link density, since the first 70% of the monomer conversion occurred in the presence of a low concentration of EGDMA and the final 30% of the reaction took place in the presence of a much higher concentration of cross-linker.

Acknowledgment. We thank Clariant Corp., Clariant Canada, NSERC Canada, and the Province of Ontario through its ORDCF program for their support of this project. We thank Dr. N. Coombs for his help in obtaining and analyzing the SEM images and Dr. J. Wu for helpful discussions. J.S.S. thanks the Province of Ontario for an OGS scholarship.

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MA050992Z