Surfactant-Free Synthesis of Cross-Linked Polymer Microspheres in Supercritical Carbon Dioxide

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ABSTRACT

Herein we report the first synthesis of a highly cross-linked polymer, poly(divinylbenzene), in supercritical CO₂. The polymer was isolated in the form of discrete microspheres (diameter = 1.5-3 µm) in good yields (\geq 90 %), even though no surfactants were used in the polymerisation process.

INTRODUCTION

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Supercritical carbon dioxide (scCO₂) is an attractive solvent for polymer chemistry because it is inexpensive, non-toxic, and non-flammable [1,2]. Unlike conventional liquid solvents, supercritical fluids (SCFs) are highly compressible and the density (and therefore solvent properties) can be tuned over a wide range by varying pressure [3]. Moreover, SCFs revert to the gaseous state upon depressurisation, greatly simplifying the separation of solvent from solute. DeSimone and others have shown that scCO₂ is a versatile solvent for both homogeneous [4-6] and heterogeneous [7-10] polymerisations. In particular, CO₂-soluble surfactants have been developed for free radical dispersion polymerisation in scCO₂, thus allowing the formation of regular polymer microspheres by this method [11-17]. Supercritical fluids have also been used to produce micron and sub-micron sized polymer particles by techniques such as rapid expansion of supercritical solutions (RESS) [18] and by precipitation with a compressed fluid antisolvents (PCA) [19].

Cross-linked polymer resins are useful in a wide range of applications, including solid phase synthesis, [20] combinatorial chemistry, [21] polymer supported reagents, [22] and molecular imprinting [23,24]. Other important uses are found in the areas of size exclusion chromatography, [25] ion-exchange resins, [26] medical diagnostics, [27] and the controlled release of drugs [28]. In all of these applications, it is often desirable to produce the cross-linked resins in the form of regular microspheres. This is usually achieved by heterogeneous methods such as suspension, dispersion, or emulsion polymerisation [29]. Typically, amphiphilic surfactants or stabilisers are used to prevent particle coalescence in these processes, however residual surfactant on the particle surfaces may sometimes impair the performance properties of the resulting polymers. We report here the first example of the surfactant-free synthesis of cross-linked polymer microparticles in scCO₂ (Scheme 1).

a
 + b

$$T = 65 \,^{\circ}\text{C}, P = 310 \text{ bar}$$
 Cross-Linked Polymer

Scheme 1: Polymerisation of divinylbenzene (DVB) in $scCO_2$. a = 0.55-0.8, b = 0.2-0.45.

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Relatively uniform poly(divinylbenzene) (PDVB) microspheres were formed *without* the addition of surfactants or stabilisers, because the particles were stabilised against coagulation by their rigid, cross-linked surfaces [30]. The reactions were classified as a suspension polymerisations under these conditions, because most of the monomer was insoluble in the CO_2 continuous phase [29,31,32].

I - MATERIALS AND METHODS

Divinylbenzene (DVB) was purchased from Aldrich as mixtures containing around Materials. 55% DVB [DVB55 = 56% divinylbenzene (meta + para isomers), 43% ethylvinylbenzene (meta + para isomers), $+ \sim 1\%$ diethylbenzene/naphthalene/inhibitor] or 80% DVB [DVB80 = 78% divinylbenzene (meta + para isomers), 20% ethylvinylbenzene (meta + para isomers), + ~ 2% diethylbenzene/naphthalene/inhibitor] respectively. Both DVB55 and DVB80 were passed down a neutral alumina column remove inhibitor before to use. 2,2'-Azobisisobutyronitrile (AIBN, Aldrich) was recrystallised twice from methanol. Styrene (Aldrich) was deinhibited and purified by vacuum distillation.

Equipment : High pressure reactions were carried out in a 10 mL stainless steel reactor, equipped with a sapphire window for observation of phase behaviour [16]. Liquid CO_2 was delivered to the reactor with a Pickel PM 101 nitrogen driven pump. The pressure in the reactor was measured with a pressure transducer (A105, RDP Electronics) and a digital display (E308, RDP Electronics). The internal reactor temperature was measured with an industrial mineral isolated thermocouple (Type K, RS Electronics). A PTFE-coated magnetic stir bar was used to mix the contents of the reactor. <u>SAFETY NOTE</u>: Observation of reactor contents should never take place directly, but only by use of a mirror.

Polymerisations: The reactor was charged with monomer (2.0 g) and AIBN (0.16 g), and the system was purged with a slow flow of CO₂ for 15-20 minutes. The reactor was then pressurised with CO_2 to 70-80 bar, stirring commenced, and the reaction mixture heated to the desired temperature (65 °C). If necessary, more CO₂ was added close to the reaction temperature until the correct conditions were obtained ($P = 310 \pm 10$ bar). The polymerisation was allowed to continue with stirring overnight. Phase behaviour in the reactor was observed closely for the first 3-4 h. Under these conditions (20 w/v% DVB55/80 in CO₂), much of the monomer was insoluble in the continuous phase, and the reaction proceeded as a suspension polymerisation [29,31,32]. The supercritical solution was initially heterogeneous, consisting of a cloudy suspension of undissolved monomer in CO_2 . With time (~ 90 min), a white solid precipitate formed on the walls and window of the reactor. At the end of each reaction, the system was cooled to ambient temperature and the CO₂ was vented slowly through acetone to trap any polymer/monomer which might otherwise escape during venting. The polymer was removed from the reactor, and the reactor was rinsed with acetone to collect all solids. A typical procedure for the purification of the cross-linked resins is as follows [30]. The polymer (~ 2 g) was washed by suspension in a solvent (~ 25 mL) followed by centrifuging and decanting. This procedure was repeated twice, both with THF and with methanol. The microspheres were then left under acetone overnight, resuspended twice in ethanol, centrifuged, decanted, and dried under vacuum at 50 °C. Yields were determined gravimetrically. There was no apparent weight loss after the washing procedure, and no soluble polymer fraction was detected.

Characterisation : Thermal analysis was carried out with a Perkin-Elmer TGA 7 in a nitrogen atmosphere. The temperature range scanned was 30 °C-800 °C at a scanning rate of 20 °C/min. Polymer morphologies were investigated with a JEOL JSM-5800 LV scanning electron microscope (SEM). The polymer powders were mounted on aluminium studs using adhesive graphite tape and sputter coated with 10-20 nm gold before analysis. Where relatively unagglomerated polymer samples were obtained, particle sizes were calculated from electron micrographs (~ 300 particle diameters measured).

Entry	% DVB ^a	Particle Size (µm) ^b	Phase behaviour ^d	Yield (%)	
1	0 ^e	agglomerated	Р	56 ^f	
2	55	1.84 (22%)	S	89	
3	80	2.40 (21%)	S	92	

II - RESULTS AND DISCUSSION

Table 1 : ^{*a*} Weight of DVB as a percentage of total monomer weight. ^{*b*} Determined by SEM. Figure in parentheses = % coefficient of variation, CV, where $CV = s/D_n \times 100$. s = standard deviation of particle diameter (mn), $D_n = mean$ particle diameter (mn). ^{*d*} P = precipitation, S = suspension. ^{*e*} 2.0 g styrene used. ^{*f*} Yield determined gravimetrically after drying sample without reprecipitation.





The results of some polymerisations in scCO₂ involving DVB as the cross-linking agent are shown in Table 1. In the absence cross-linker, of a the unstabilised precipitation polymerisation of styrene in $scCO_2$ gave low molecular weight poly(styrene) in poor vield (entry 1), as observed previously [15,17]. However, the polymerisations of DVB55 (entry 2) and DVB80 (entry 3) led to crosslinked polymers which were isolated in high yields directly from the reactor as dry, white, free-flowing powders. When the material was examined by scanning electron microscopy (SEM), it was found that the existed in the form of polymers relatively uniform microspheres (diameter = $1.5-3 \mu m$), even though no stabilisers were used 1). (Figure

This is consistent with studies by Li and Stöver, who found that highly cross-linked PDVB microspheres could be formed by precipitation polymerisation of DVB in acetonitrile [30]. In their work, it was assumed that the particle formation and growth mechanism was similar to that of dispersion polymerisation, except that the particles were stabilised against

coagulation by their rigid, cross-linked surfaces rather than by added stabilisers.

We also attribute the lack of agglomeration in our samples to the rigidity of the polymer microspheres. The fact that the more highly cross-linked samples were the least coagulated is consistent with this idea. Li and Stöver observed a precipitation polymerisation (*i.e.*, initiator and monomer were initially soluble in acetonitrile),[30] however we observed that much of the DVB monomer mixture was insoluble in scCO₂ from the start of the reaction. The initiator (AIBN) was soluble in both the monomer phase and in the CO₂ continuous phase, thus making the precise classification of the reaction as emulsion or suspension polymerisation somewhat difficult. We will refer to these reactions as suspension polymerisations, [31,32] because the particles formed were larger than 1 μ m, which is a commonly accepted arbitrary dividing between emulsion and suspension techniques [29]. The cross-linked particles had sizes similar to poly(styrene) particles formed by dispersion polymerisation in $scCO_2$ in the presence of surfactants, [15,17] although there was somewhat more evidence of particle agglomeration, particularly in less highly cross-linked samples. Thermal analysis showed the cross-linked resins to have high thermal stability; almost no thermal decomposition was observed below 400 °C. The polymers were completely insoluble in all solvents tested, however they were readily dispersed in most common organic media (except pure water) to form milky white suspensions which were stable for periods of between 30 min and several hours. The fact that the particles could be suspended in this manner can be attributed to the lack of aggregation and the absence of any undesirable surfactants on the particle surfaces.

III - CONCLUSION

Cross-linked poly(divinylbenzene) microparticles can be synthesised in $scCO_2$ in high yields without the use of any added surfactants. Carbon dioxide is an attractive solvent for this process because it is non-toxic, inert, and can be easily separated from the products; upon completion of the reaction, the CO_2 is simply vented to leave the polymer as a dry powder. One might also exploit the swelling properties of $scCO_2$ to generate macroporous cross-linked networks. At high cross-linking ratios, polymers are formed as relatively uniform microspheres (diameter = $1.5-3 \mu m$) and have good thermal stability. The effects on the polymerisation of cross-linker ratio, monomer concentration, and mechanical agitation will be described in a forthcoming publication. The synthesis of a variety of cross-linked copolymers is currently under investigation, as is the preparation of specialised functional polymers for a variety of applications.

IV - ACKNOWLEDGEMENT

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