Dispersion Atom Transfer Radical Polymerization of Vinyl Monomers in Supercritical Carbon Dioxide

Bruno Grignard,[†] Christine Jérôme,[†] Cédric Calberg,[†] Robert Jérôme,[†] Wenxin Wang,[‡] Steven M. Howdle,[‡] and Christophe Detrembleur*,[†]

Centre for Education and Research on Macromolecules (CERM), University of Liège, Sart Tilman, 4000, Liège, Belgium, and School of Chemistry, University of Nottingham, Nottingham, NG7 2RD, United Kingdom

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ABSTRACT: Controlled dispersion atom transfer radical polymerization (ATRP) of methyl methacrylate (MMA) was successfully carried out in supercritical carbon dioxide in the presence of aminated fluoropolymers. These materials played the dual role of macroligand for the copper bromide and also steric stabilizer to support formation of polymer microspheres. The livingness of the PMMA beads was confirmed by the one-pot two-step PMMA chain extension and the synthesis of poly(methyl methacrylate)-*b*-poly(2,2,2-trifluoroethyl methacrylate) (PMMA-*b*-PFMA) diblock copolymer in $scCO_2$. Successful activator generated by electron transfer (AGET) for ATRP of MMA, using tin ethylhexanoate as a reducing agent, is also discussed, and the concept of dispersion ATRP of MMA was successfully extended to the controlled dispersion polymerization of styrene by ATRP leading to the formation of PS microparticles. Finally, due to the high solubility of the catalyst in $scCO_2$, the purification of PMMA was investigated by supercritical fluid extraction, leading to the preparation of PMMA beads with low residual catalyst traces.

1. Introduction

Due to unique characteristic features of nontoxicity, nonflammability, low cost, and availability with high purity,[1] rapidly increasing attention has been paid to supercritical carbon dioxide as a solvent for polymer synthesis. Carbon dioxide is generally inert, allowing polymers to be synthesized by a variety of techniques including free radical polymerization,[2−21] cationic polymerization,[22−24] transition metal catalysis,[25,26] ring opening polymerization,[27−31] and enzymatic polymerization.[27,32,33] Moreover, CO_2 returns back to the gaseous state upon depressurization of the reactor, and polymer product recovery is straightforward. Free radical polymerization in supercritical carbon dioxide was extensively studied during the past decade, particularly for amorphous fluoropolymers,[34−38] which are highly soluble in this medium. In parallel, effort was devoted to the heterogeneous precipitation or dispersion free radical polymerization of vinyl monomers.[39−41] All these contributions focused, however, on the synthesis of homopolymers and random copolymers. Because of the increasing need for polymers with well-defined architecture (diblock-, graft-, star-shaped copolymers), molecular weight, and functional end-groups, the use of controlled radical polymerization (CRP) in $scCO_2$ has started to gain attention. Atom transfer radical polymerization (ATRP) is a very well established CRP technique, well-suited to a wide range of monomers, including styrene and styrene derivatives, (meth)acrylates, and (meth) acrylonitrile. There are a few reports of ATRP in $scCO_2$. Desimone and Matyjazewski were the first to consider homogeneous ATRP of perfluorooctyl methacrylate (FOMA) in this medium using a CO_2-soluble copper catalyst.[42] Later, Okubo et al. investigated the possibility of preparing diblock copolymers in this medium starting from a PDMS macroinitiator.[43] Finally, Howdle et al. recently published results on the "one-pot" synthesis of PCL-*b*-PMMA diblock copolymers by combining the enzymatic ring-opening polymerization of ϵ-caprolactone and the copper-mediated ATRP of MMA.[44−47] More recently, further studies have reported the use of RAFT dispersion polymerization in $scCO_2$.[48]

In a very recent communication, we reported the first efficient dispersion ATRP of methyl methacrylate (MMA) in $scCO_2$ using a fluorinated macroligand that had a dual role, that is, the complexation of the copper salt and the stabilization of PMMA growing particles.[50] In this paper, we investigate much further and extend this new system to the dispersion synthesis of block copolymers, to activator generated by electron transfer (AGET) for ATRP and to the dispersion ATRP of styrene in $scCO_2$. The influence of the composition and molecular weight of the macroligand on the polymerization control will also be investigated. Finally, the purification of the polymer by supercritical fluid extraction of the ATRP catalyst ligated by the macroligand will be reported.

2. Results and Discussion

2.1. Dispersion ATRP of Methylmethacrylate. The primary requirement for the successful implementation of ATRP in $scCO_2$ is the solubility of the organometallic complex in this medium. It is the reason why fluorinated macroligands, of the general structure shown in Scheme 1, were synthesized and converted into the CO_2-philic copper(I) complexes.[49] Tetraethyldiethylenetriamine (TEDETA) units were thus the complexing groups.

The ATRP of MMA was initiated by methyl-α-bromophenylacetate (MBPA) at 70 °C and 320 bar in the presence of copper bromide ligated by a fluorinated macroligand (M_n = 15000 g/mol; 3 TEDETA units/chain; [MBPA]/[TEDETA] = 2; [CuBr]/[TEDETA] = 1). After 24 h, PMMA with well-defined molecular weight and narrow molecular weight distribution was produced with a controlled manner.[50] Nevertheless, the key role of the fluorinated macroligand in the dispersion ATRP of MMA in supercritical carbon dioxide is expected to depend on its composition and molecular weight.[40,39] This basic question was addressed by repeating the ATRP of MMA under the same conditions as in the previous experiments, except for the number of amino-ligands (TEDETA) attached to fluorinated

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* To whom correspondence should be addressed. Tel.: (32)4-3663465. Fax: (32)4-3663497. E-mail: christophe.detrembleur@ulg.ac.be.

[†] University of Liège.

[‡] University of Nottingham.

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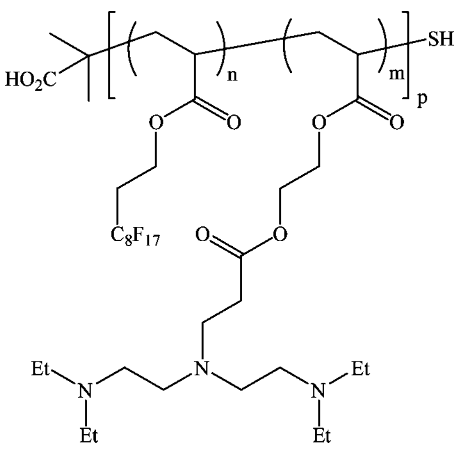
Scheme 1. General Structure of the Amino-fluorinated Macroligands



poly(acrylate) chains of constant M_n (15000 g/mol). Table 1 shows that the polymerization is faster when conducted in the presence of a macroligand with three TEDETA units per chain, although the initiator efficiency is slightly lower in this case.

The experimental dependence of the polymerization rate on the TEDETA content of the macroligand probably results from a more or less complex influence of several parameters, including accessibility to the catalytic sites, proximity effects, and solubility of the macroligand. The increase in the TEDETA content (from 2 to 3) would improve the access of the growing chain to the catalytic sites, thereby accounting for a higher monomer conversion. A further increase in the number of TEDETA per chain (up to 4) has a deleterious effect on the polymerization kinetics. This may be caused by two possibilities. First, the TEDETA substituent and their complexes with CuBr decrease the solubility of the macroligand in $scCO_2$. Moreover, the monomer (MMA) could act as a cosolvent such that the solubility of the ligated catalyst would decrease as the monomer is consumed.[51−54] Loss of the less soluble chains, that is, those of higher molecular weight or of higher TEDETA content should decrease the polymerization rate. A second explanation can be found in the proximity effect, as reported by Van Koten et al. for atom transfer radical addition.[55] This states that at higher TEDETA content, the probability for two radicals to be in very close proximity is increased and so is the chance for them to be terminated irreversibly and for the oxidized catalyst (M_t^{n+1}) to accumulate in the polymerization medium. The equilibrium between active and dormant species is then shifted toward the dormant species and the polymerization is slowed down.

Whatever the macroligand composition, PMMA was collected as microspheres, which demonstrates that the macroligand has a dual role, that is, the complexation of the copper salt and the stabilization of PMMA growing particles.[50] Examples of particles formed with the assistance of macroligands with M_n = 15000 g/mol and different TEDETA contents (2, 3, and 4 TEDETA units/chain, 400 rpm) are illustrated in Figure 1A−C.

Quasi-spherical large particles (200−400 μm) were formed in the presence of 10 wt % of the macroligand containing two TEDETA units/chain ([MMA]/[MBPA] = 400; Figure 1A). For the sake of comparison, DeSimone et al.[56−61] and Howdle et al.[40,62−65] prepared spherical PMMA microparticles with a narrow size distribution and an average diameter smaller than 5 μm by free radical dispersion polymerization of MMA in $scCO_2$ with an appropriate stabilizer. It thus appears that this macroligand with two TEDETA units/chain is not a very effective stabilizer of the insoluble PMMA. When the TEDETA content is increased from 2 to 3 per chain, the amount of macroligand must be decreased from 10 to 7.75 wt % (compared to MMA), to maintain the content of ligated CuBr constant. In these conditions, small spherical particles with an average size from 5 ± 0.7 μm coexist with a minor fraction of larger microspheres (15 ± 2.7 μm; Figure 1B). Figure 1C shows that the average size of the PMMA particles increases when the macroligand with four TEDETA per chain is used: small PMMA particles with an average diameter of 10 ± 2.5 μm coexist with larger particles of 17 ± 3.2 μm. The reason for the increase of the particles size has to be found in the macroligand content, which is also the stabilizer, that has decreased down to 5 wt % when a macroligand of higher TEDETA composition (at constant molecular weight) is used to complex copper bromide.

At constant TEDETA content, the chain length of the macroligand could also affect both the polymerization control and the stabilization of the growing particles. Indeed, at constant pressure and temperature, the solubility of the ligated catalyst and the efficiency of the steric barrier around the particles are expected to change with the molecular weight of the macroligand. Effect of molecular weight of the macroligand on the control of the ATRP of MMA initiated by methyl-α-bromophenylacetate (MBPA) and catalyzed by copper(I) bromide at 320 bar and 70 °C was then investigated. M_n and TEDETA content of the fluorinated macroligand were as follows: M_n = 5000 g/mol with two TEDETA/chain; M_n =10000 g/mol with three TEDETA/chain and M_n = 15000 g/mol with four TEDETA/chain. In all the experiments, [MBPA]/[TEDETA] was 2, [CuBr]/[TEDETA] was 1, and the rate of stirring was 400 rpm. The experimental data are reported in Table 2. At a constant [MMA]/[MBPA] molar ratio of 200, there is no significant difference in the monomer conversion and in the polydispersity index after 24 h. However, when ATRP is conducted in the presence of a macroligand of M_n = 10000 g/mol with three TEDETA/chain, a low initiator efficiency ($f = M_{n,th}/M_{n,exp} = 0.5$) was measured. Nevertheless, this result should be confirmed by further investigation.

At the constant [MMA]/[MBPA] molar ratio of 200 (entries 1, 5, 6, Table 2), PMMA microspheres were collected, regardless of the molecular weight of the macroligand upon slow release of CO_2. Figure 2 shows that particles with a much larger diameter (100 ± 9 μm) were formed in the presence of the shorter macroligand (M_n = 5000 g/mol with two TEDETA units per chain, Figure 2A). The higher heterogeneity in the particles size was noted for the intermediate macroligand of M_n = 10000 g/mol bearing three TEDETA units per chain (Figure 2B). In these conditions, PMMA micropsheres with a diameter of 12 ± 5.1 μm coexist with a minor fraction of large particles of 100 ± 10.5 μm. Finally, the smaller and more homogeneous particles (14 ± 4.6 μm) were observed with the higher M_n (15000 g/mol) macroligand (four TEDETA units per chain), that was apparently the better stabilizing agent (Figure 2C).

As a rule, when the same macroligand of M_n = 5000 g/mol with two TEDETA/chain was used and the [MMA]/[MBPA] was increased (entries 1, 3 and 4, Table 2), the control of the polymerization seemed to be lost as indicated by a dramatic increase in the polydispersity from 1.2 to 2.3. In parallel, stable PMMA particles were no longer collected, which suggests that the polymerization control is directly dependent on the proper dispersion of the insoluble growing chains. These results were confirmed by conducting the ATRP of MMA in the same conditions but using free TEDETA instead of a macroligand to complex copper bromide. In these conditions, the polymerization was not controlled and PMMA was collected as a single monolithic block or “chunk” of polymer.[50]

2.2. Chain Extension and Synthesis of Block Copolymer.

Livingness of the ATRP of MMA in the presence of CuBr ligated by a fluorinated macroligand (M_n = 15000 g/mol, three TEDETA/chain) was first investigated by the resumption of the

Table 1. Experimental Conditions for ATRP of MMA in $scCO_2$ (70 °C, 320 bar, 24 h)

macroligand							
M_n(g/mol)	Nr of TEDETA units	[MMA]/[MBPA]	$M_{n,th}$[a](g/mol)	$M_{n\ exp}$[b] (g/mol)	conv.[c] (%)	f[d]	PDI
15000	2	400	28000	36000	69	0.73	1.15
15000	3	400	37000	59000	93	0.63	1.20
15000	4	400	31000	41000	78	0.75	1.20

[a] $M_{n,th}$ = (weight of monomer/n initiator) × monomer conversion. [b] By SEC with a PMMA calibration. [c] Determined gravimetrically. [d] $f = M_{n,th}/M_{n,exp}$.

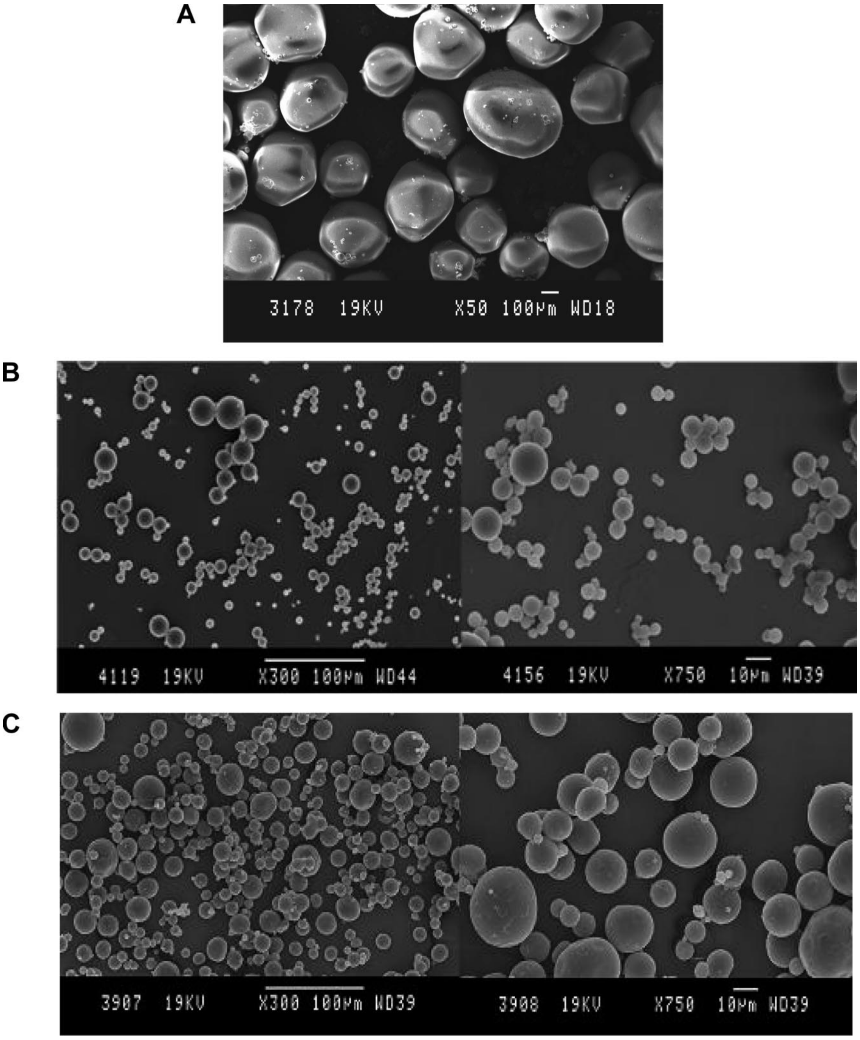


Figure 1. (A) SEM picture of PMMA formed by dispersion ATRP of MMA in the presence of 10 wt % of a macroligand (M_n = 15000 g/mol) with two TEDETA units/chain ([MMA]/[MBPA] = 400). (B) SEM pictures of PMMA formed by dispersion ATRP of MMA in the presence of 7.75 wt % of a macroligand (M_n = 15000 g/mol) with three TEDETA units/chain ([MMA]/[MBPA] = 400). (C) SEM pictures of PMMA formed by dispersion ATRP of MMA in the presence of 5.3 wt % of a macroligand (M_n = 15000 g/mol) with four TEDETA units/chain ([MMA]/[MBPA] = 400).

Table 2. Effect of Molecular Weight of the Macroligand on the ATRP of MMA in $scCO_2$ (P = 320 bar, T = 70 °C

	macroligand								
entry	M_n (g/mol)	Nr TEDETA units	time (h)	[MMA]/ [MBPA]	$M_{n,th}$[a] (g/mol)	$M_{n,exp}$[b] (g/mol)	conv.[c] (%)	f[d]	PDI
1	5000	2	24	200	18000	29000	89	0.63	1.20
2	5000	2	18	400	27500	40000	68	0.68	1.20
3	5000	2	24	600	46000	43000	76	1.00	1.90
4	5000	2	24	800	59000	67000	74	0.88	2.30
5	10000	3	24	200	17000	35000	85	0.50	1.15
6	15000	4	24	200	17000	29000	85	0.60	1.15

[a] $M_{n,th}$ = (weight of monomer/n initiator) × monomer conversion. [b] SEC with PMMA calibration. [c] Gravimetrically determined. [d] $f = M_{n,th}/M_{n,exp}$.

MMA polymerization. For this purpose, a special high pressure reactor equipped with additional valves was used. One valve allows for the injection under pressure of the second MMA feed and the second valve allows for analytical samples to be withdrawn periodically from the high pressure cell under pressure, without negatively affecting the reaction.[48] Polymerization of MMA was first conducted in a 15 mL high pressure cell in $scCO_2$ at 80 °C and 320 bar with a stirring rate of 400 rpm. The macroligand (three TEDETA/chain, 15000 g/mol) was used to complex copper(I) bromide. After 24 h of polymerization

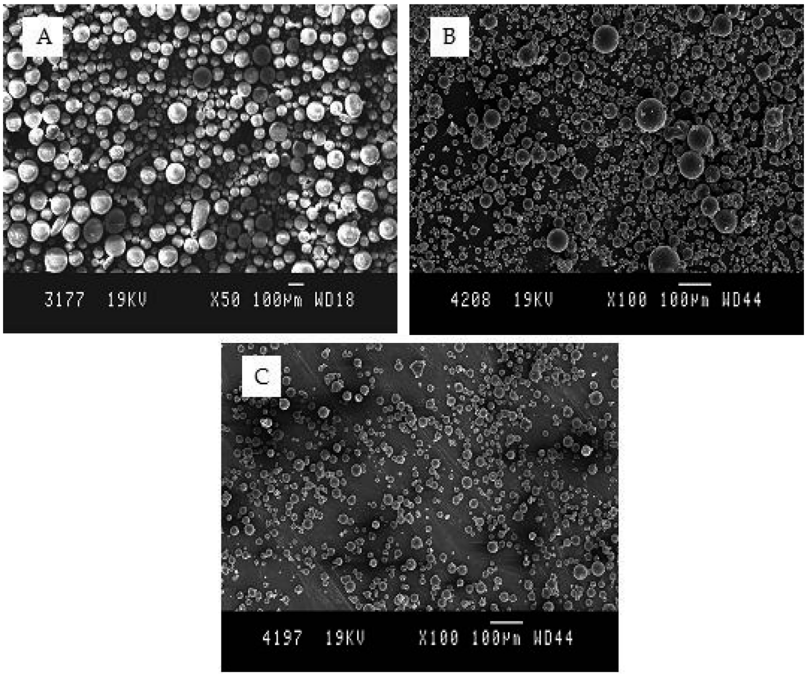


Figure 2. SEM pictures of PMMA prepared by dispersion ATRP of MMA. Effect of molecular weight of the macroligand on the particles stabilization ([MMA]/[MBPA] = 200): (A) macroligand with M_n = 5000 g/mol and two TEDETA units/chain (entry 1, Table 3); (B) macroligand with M_n = 10000 g/mol and three TEDETA units/chain (entry 5, Table 3); (C) macroligand with M_n = 15000 g/mol and four TEDETA units (entry 6, Table 3).

Table 3. Resumption of the MMA Polymerization

PMMA macroinitiator				PMMA resumption			
conv.[a] (%)	$M_{n,th}$[b](g/mol)	$M_{n,exp}$[c](g/mol)	PDI	conv.[a] (%)	$M_{n,th}$[b](g/mol)	$M_{n,exp}$[c] (g/mol)	PDI
90	18000	28000	1.25	65	44000	63000	1.35

[a] Gravimetrically determined. [b] $M_{n,th}$ = (weight of monomer/n initiator) × monomer conversion. [c] Estimated by SEC with PMMA calibration.

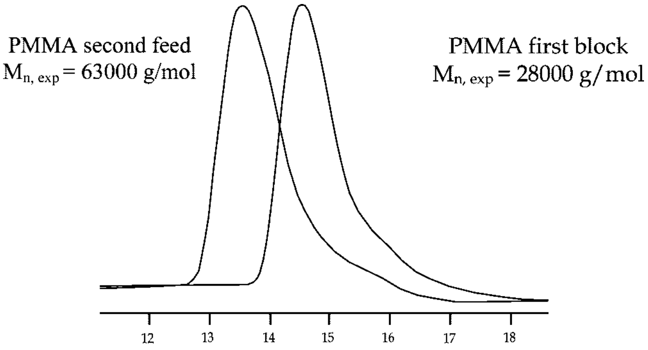


Figure 3. SEC traces of PMMA before and after the polymerization of a second MMA feed.

with [MMA]/[MBP] = 200, [CuBr]/[MBP] = 0.5, a sample was picked out. The monomer conversion was measured by NMR spectroscopy (90%) and the molecular weight was estimated by size exclusion chromatography (M_n = 28000 g/mol). Then a second monomer feed of MMA was added under pressure and the pressure was maintained at 320 bar. After 24 h of polymerization, the reactor was cooled and CO_2 was slowly vented. The monomer conversion, gravimetrically determined, was 65%, and the final polymer was analyzed by size exclusion chromatography (Table 3). The SEC trace of the polymer collected after chain extension (Figure 3) was clearly shifted toward higher molecular weight, which is consistent with a nearly quantitative reinitiation of the polymerization after addition of the second monomer feed. Indeed, a small tailing toward the lower molecular weight side is observed in the SEC trace that probably results from the presence of some dead chains. The presence of some dead chains is consistent with the experimental molecular weight which is higher than the theoretical one. It is, however, important to note that the conversion reached for the macroinitiator was high (~90%), which might reasonably account for the formation of some dead chains.

After the polymerization resumption, spherical particles with a diameter in the 5−80 µm range were recovered with, however, a broad size distribution (Figure 4).

The origin for the broad size distribution of the PMMA particles could be found in the possible dissolution of part of the originally formed particles within the second monomer feed. The important information inferred from the resumption of the MMA polymerization is that the PMMA chains formed in $scCO_2$ remain active after synthesis and can thus be used as macroinitiators for the synthesis of diblock copolymers in this medium.

Because block copolymers with a constitutive fluorinated block are of interest in coating applications and as stabilizers for dispersion or emulsion polymerization conducted in supercritical carbon dioxide, the synthesis of poly(methyl methacrylate)-*b*-poly(2,2,2-trifluoroethyl methacrylate) (PMMA-*b*-PFMA) diblock copolymers was therefore investigated in $scCO_2$ by using the macroligand (three TEDETA/chain, 15000 g/mol)/copper catalytic system. MMA was first polymerized in $scCO_2$ at 80 °C and 320 bar in a 15 mL high pressure cell ([MMA]/[initiator] = 200, [CuBr]/[initiator] = 0.5) under stirring (400 rpm). After 24 h, a sample was withdrawn for characterization (90% conversion), and the second monomer (FMA) was injected and polymerized for 24 h under the same conditions as for MMA resumption. Figure 5 shows that the SEC trace of PMMA first block is shifted toward the higher molecular weight as a result

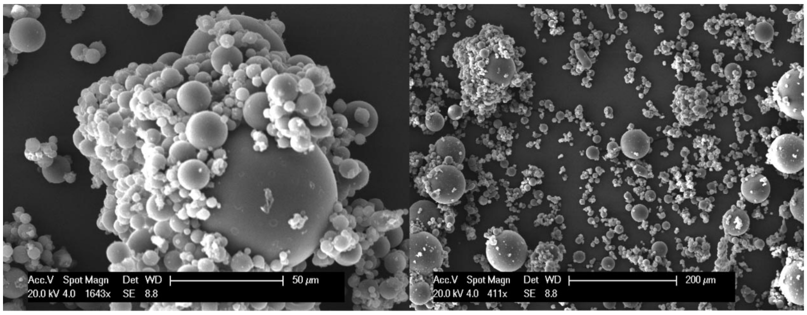


Figure 4. SEM pictures of PMMA formed as result of the polymerization resumption of MMA (80 °C, 400 rpm and 320 bar for 48 h). The macroligand ($M_n = 15000$ g/mol, three TEDETA/chain) was used to complex copper bromide.

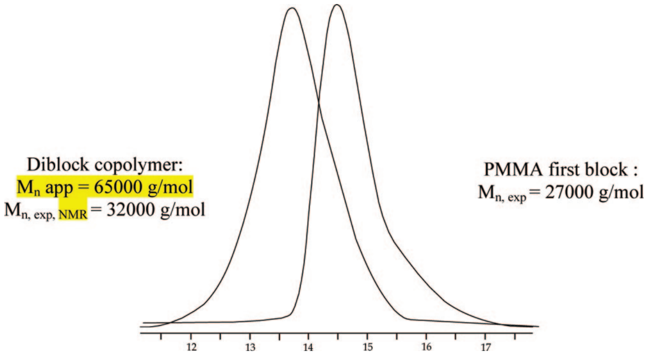


Figure 5. SEC trace for the PMMA first block and the PMMA-*b*-PFMA diblock copolymer, respectively.

of the polymerization of FMA, which demonstrates the formation of a PMMA-*b*-PFMA copolymer. Moreover, the polydispersity remains reasonably low ($M_w/M_n = 1.40$). Table 4 summarizes the data collected for the synthesis of PMMA-*b*-PFMA in $scCO_2$ in a one-pot process.

Most exciting, the diblock copolymer was collected as spherical particles with a diameter in the 70 ± 20 μm range, meaning that PMMA "living" beads were produced (Figure 6). This has not been achieved before using ATRP and is likely the result of the very effective mass transport properties of $scCO_2$. The data in Table 5 and Figure 6 are consistent with the fast penetration of the PMMA particles by the fluorinated methacrylate and the resumption of the FMA polymerization by the PMMA chains whatever their location in the particles. This very favorable situation is the consequence of the high diffusivity, the high transport properties and the plasticizing effect[66] of supercritical CO_2.

Further experiments are now under investigation in order to optimize the one-pot two-step synthesis of PMMA-based diblock copolymers in supercritical carbon dioxide.

2.3. AGET ATRP in Dispersion. Activator generated by electron transfer (AGET) for ATRP was proposed to overcome the drawback of ATRP related to the oxidation of the catalyst in the presence of oxidizing agents.[67−70] Although many reducing agents can be used to reduce the catalyst to its active form, tin(II) 2-ethylhexanoate ($Sn(EH)_2$) was chosen to reduce Cu(II) because it is known to have high solubility in $scCO_2$. Indeed, $Sn(EH)_2$ was successfully used as a catalyst for the ring opening polymerization of ϵ-caprolactone in this medium.[71] In practice, AGET ATRP of MMA was initiated by MBPA and catalyzed by $CuBr_2$ ligated by a macroligand of 15000 g/mol bearing four TEDETA/chain. Different initiator/Cu(II)/Sn(II) molar ratios were investigated to optimize the AGET ATRP of MMA in $scCO_2$ (Table 5). For each experiment, the monomer conversion was gravimetrically determined, and the molecular weight and the polydispersity were determined by SEC.

When a MBPA/Cu(II)/Sn(II) molar ratio of 1/1/0.25 is used (Table 5, entry 1), the polymerization is not controlled, the polydispersity was high and the experimental molecular weight value was different from the theoretical one. By increasing the amount of tin from 0.25 to 0.5 (Table 5, entry 2), the control of the polymerization was significantly improved. Indeed, in these conditions, the monomer conversion was still high; the experimental molecular weight is in good agreement with the theoretical value and the polydispersity decreases from 2 to 1.49. After slow release of the pressure, PMMA was collected as a powder that consists of very large elongated particles (∼1 mm, Figure 7).

Finally, for the sake of comparison, the AGET ATRP of MMA was repeated in the optimized conditions described by Matyjaszewski in the case of AGET ATRP of MMA in solution.[67] Then, when a MBPA/Cu(II)/Sn(II) molar ratio of 1/0.4/0.18 is used (Table 5, entry 3), the monomer conversion was lower, but the polymerization was still controlled and the polydispersity decreases to 1.33. Nevertheless, in these conditions, PMMA was not collected as a powder because of the low MMA conversion.

2.4. Dispersion ATRP of Styrene. The concept of dispersion ATRP of MMA using a macroligand that acts as both a stabilizer and a complexing species for the copper salt was extended to styrene (St). To demonstrate that the macroligands are effective stabilizers for PS growing particles, the conventional free-radical polymerization of styrene, initiated by AIBN (1 wt % compared to St), was first conducted in $scCO_2$ at 340 bar and 65 °C for 24 h. After slow release of the pressure, PS was collected as small size microspheres with a mean diameter of 1.55 ± 0.39 μm ($M_n = 90000$ g/mol; $M_w/M_n = 1.95$; Figure 8).

The ATRP of styrene was initiated by phenylethyl-2-bromide (PEBr) at 340 bar in the presence of copper bromide ligated by a fluorinated macroligand ($M_n = 15000$ g/mol; four TEDETA units/chain; [PEBr]/[TEDETA] = 1; [CuBr]/[TEDETA] = 1, [St]/[PEBr] = 385) and conducted at different temperatures, that is, 70, 80, and 100 °C (Table 6). When ATRP was conducted at 100 °C, the monomer conversion, gravimetrically determined, was high after 2 days (90%), the experimental molecular weight value, estimated by size exclusion chromatography, was in good agreement with the theoretical one and the polydispersity was low (1.15) (Table 6, entry 7). However, at 100 °C, PS is plasticized and the polymer was collected as a monolithic chunk of material after release of the pressure rather than the preferred powder. By decreasing the temperature from 100 to 70 °C, the polymerization was still controlled (Table 6, entries 1−3) but the polymerization rate was very slow (monomer conversion of 90% after 6 days). Interestingly, in these conditions and at high conversion, PS was collected as a powder that consists of quasi-spherical particles of large diameter (>100 μm). Finally, by increasing the temperature from 70 to 80 °C (Table 6, entry 6), the polymerization rate was

Table 4. Synthesis of a PMMA-*b*-PFMA Diblock Copolymer

PMMA first block				PFMA second block			PMMA-*b*-PFMA diblock copolymer	
conv.[a] (%)	$M_{n,th}$[b](g/mol)	$M_{n,exp}$[c](g/mol)	PDI	conv.[a] (%)	$M_{n,th}$[d] (g/mol)	$M_{n,^1H\ NMR}$[e](g/mol)	$M_{n,app}$[c](g/mol)	PDI
90	18000	27000	1.25	32	5400	4800	65000	1.40

[a] Gravimetrically determined. [b] $M_{n,th}$ = (weight of monomer/*n* initiator) × monomer conversion. [c] Estimated by SEC with a PMMA calibration. [d] $M_{n,th}$ = (weight of monomer/*n* initiator) × monomer conversion. [e] Estimated by ^{1}H NMR spectroscopy from the relative intensity of protons typical of the MMA unit (CH_3, $\delta = 3.7$ ppm) and the FMA unit (CH_2, $\delta = 4.63$ ppm), respectively. Combined to $M_{n,PMMA}$, the diblock composition (determined by ^{1}H NMR) allows $M_{n,PFMA}$ to be calculated.

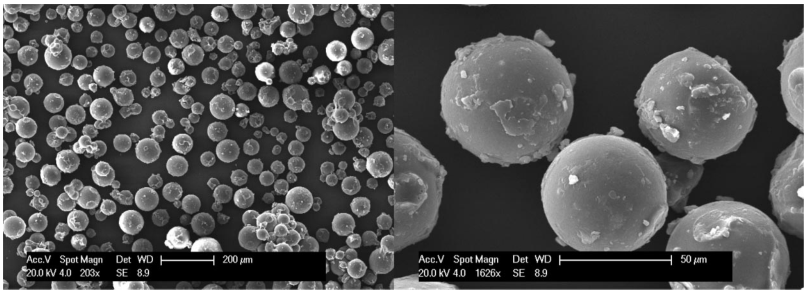


Figure 6. SEM pictures of the PMMA-*b*-PFMA microparticles formed in a one-pot two step strategy in $scCO_2$.

Table 5. Experimental Conditions for the AGET ATRP of MMA in $scCO_2$ (P = 320 bar, 70 °C, 24 h, 400 rpm)

entry	[MMA]/[MBPA]	MBPA/CuII/SnII	conv.[a] (%)	$M_{n,th.}$ (g/mol)	$M_{n,SEC}$[b] (g/mol)	M_w/M_n
1	400	1/1/0.25	90	36000	27000	2
2	400	1/1/0.5	90	36000	37000	1.49
3	400	1/0.4/0.18	25	10000	11600	1.33

[a] Gravimetrically determined. [b] Estimated using a PMMA standard calibration.

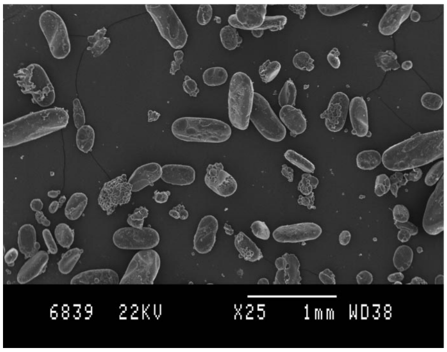


Figure 7. SEM pictures of PMMA prepared by AGET ATRP in $scCO_2$: [MMA]/[MBPA] = 400, macroligand of M_n = 15000 g/mol and four TEDETA units/chain, P = 320 bar, 70 °C, 24 h (entry 2, Table 5).

increased (monomer conversion of 90% after 3 days), while keeping the polymerization control, and after depressurization, PS was collected as large quasi-spherical particles with a diameter ranging from 100 to 300 μm. Finally, different monomer to initiator molar ratios were investigated to prepare PS with different molecular weights (Table 6, entries 3−5). At low [sty]/[PEBr], after 6 days, the monomer conversion was high and the experimental molecular weight was in good agreement with the theoretical value. By increasing the [sty]/[PEBr] molar ratio from 190 to 575, despite a drastic decrease of the polymerization rate (monomer conversion = 20% after 6 days), the polymerization still remained controlled.

2.5. Polymer Purification by Supercritical Fluid Extraction. The major drawback of ATRP is the presence of catalyst residues in the final polymer that may lead to toxicological and environmental problems. Therefore, the removal of the supported copper, that was demonstrated to be highly soluble in $scCO_2$, was investigated by supercritical fluid extraction. In a typical procedure, polymerization of MMA was initiated by methyl-α-bromophenylacetate at 320 bar and 70 °C in the presence of copper bromide ligated by a macroligand with four TEDETA per chain (M_n = 15000 g/mol; [MMA]/[TEDETA] = 200, [MBPA][CuBr] = 2) for 24 h. The polymerization was carried out at 400 rpm within a high pressure cell equipped with a mechanical stirrer and a heating mantle. At the end of the polymerization, the PMMA microspheres rapidly settled on the bottom of the reactor when stirring was stopped, whereas the CO_2-philic macroligand remains soluble. To prevent the transition metal from being oxidized by oxygen, the catalyst was removed by venting the reactor with CO_2 at a flow rate of 5 mL/min through a second high pressure vessel in which the CO_2 pressure was 1 bar. As a result of the dramatic drop in the pressure, the catalyst precipitated in the second vessel as a green polymer. The effect of the elution volume on the extraction yield was determined. After catalyst extraction and complete depressurization of the high pressure cell, the residual copper in PMMA was estimated by inductively coupled plasma (ICP). The effects of the molecular weight of the catalyst, the temperature, the elution volume, and the elution rate on the extraction yields of copper were investigated.

Effect of the elution volume on the extraction yields was first investigated. Data in Table 7 (entries 1−3) show that 200 mL of CO_2 are enough for 75% of the catalyst to be extracted. Surprisingly, a further increase in the elution volume from 200−800 mL does not improve the extraction yield of the catalyst. A reason might be the coalescence of the PMMA microspheres (without stirring). Indeed, PMMA was collected as a bulk polymer after extraction as a result of the plasticizer effect of the CO_2 at 70 °C.[66] This dramatic decrease in the surface/volume ratio of PMMA must have an adverse effect on the catalyst extraction.

The effect of the macroligand molecular weight, at constant TEDETA composition, on the extraction yield of the ligated catalyst was also investigated. The extraction data at 70 °C and 300 bar are reported in Table 7 (entries 2−5). At constant elution volume, a decrease in the macroligand molecular weight while keeping the TEDETA composition constant is beneficial to the extraction yield of the catalyst. Indeed, more than 90% of the catalyst is removed when a short macroligand in used to

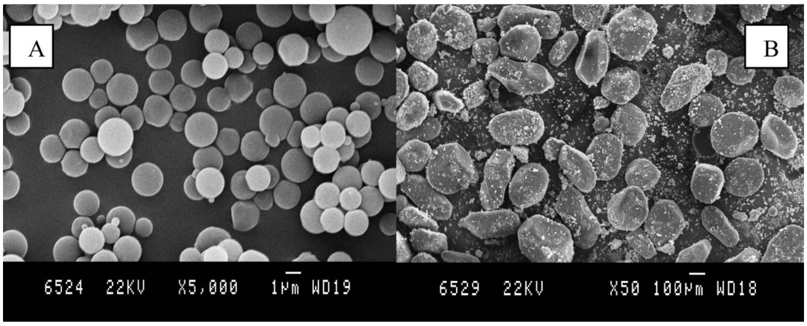


Figure 8. (A) PS particles prepared by conventional free-radical polymerization in dispersion using a macroligand (15000 g/mol, four TEDETA/chain, 10 wt % compared to MMA) as stabilizer and (B) PS particles obtained by dispersion ATRP of styrene (Table 6, entry 3).

Table 6. Experimental Conditions for the Dispersion ATRP of Styrene in $scCO_2$ at Different Temperatures (P = 340 bar)

entry	[sty]/[PEBr]	[PEBr]/[Cu]	time (h)	T (°C)	conv.[a] (%)	$M_{n,th}$ (g/mol)	$M_{n,exp}$[b] (g/mol)	PDI
1	385	1	24	70	15	6000	7000	1.21
2	385	1	48	70	38	15000	18000	1.19
3	385	1	144	70	98	39000	43000	1.22
4	190	1	144	70	97	19000	22000	1.15
5	575	1	144	70	20	12000	11000	1.32
6	385	1	72	80	96	38000	39000	1.23
7	385	1	48	100	89	36000	38000	1.15

[a] Gravimetrically determined. [b] Estimated by SEC with a PS calibration.

Table 7. Effect of the Elution Volume, Macroligand Molecular Weight, and Temperature on the Catalyst Extraction Yield ([MBPA]/[CuBr] = 2, [MMA]/[MBPA] = 200, 70 °C, 24 h, 400 rpm, $[Cu]_0$ = 4314 ppm)

	macroligand characteristics		PMMA characteristics			catalyst extraction					
entry	M_n (g/mol)	Nr TEDETA units/chain	M_n[a] (g/mol)	PDI	conv.[b] (%)	temp. (°C)	P (bar)	flowrate (mL/min)	CO_2 volume (mL)	residual catalyst (ppm)	% extracted catalyst
1	15000	4	28000	1.15	85	70	300	5	200	1100	75
2	15000	4	25000	1.25	85	70	300	5	400	1450	67
3	15000	4	28000	1.1	90	70	300	5	800	1230	72
4	10000	3	31000	1.15	94	70	300	5	400	279	93
5	10000	3	30000	1.1	87	70	300	5	800	405	90
6	15000	4	29000	1.15	90	50	300	5	400	430	90
7	10000	3	23000	1.25	80	50	300	5	400	158	96

[a] Estimated by SEC with PMMA calibration. [b] MMA conversion determined gravimetrically.

complex the copper catalyst. These results are consistent with the higher solubility and the faster diffusion through PMMA of a shorter macroligand at constant TEDETA content.

The temperature is also thought to affect the extraction yield of the catalyst. To answer this question, the extraction of the ligated catalyst was carried out at 50 °C instead of 70 °C as before. Under these conditions, the solvent strength was drastically modified. Indeed, a decrease in temperature, while keeping constant the CO_2 pressure, increases the CO_2 density and, thus, the solvent power of the supercritical fluid. Whatever the molecular weight and composition of the macroligand, copper is more efficiently extracted at the lower temperature (Table 7, entries 2 and 6; 4 and 7). Indeed, more than 95% of the ligated catalyst was removed at 50 °C in case of the macroligand with three TEDETA units/chain and M_n = 10000 g/mol. Clearly, the enhanced solubility at lower temperature accounts for the improved extraction of the ligated catalyst. Moreover, when the extraction is conducted at 50 °C instead of 70 °C, the PMMA microspheres do not coalesce anymore as a monolithic chunk of material, which is also favorable to the extraction efficiency.

3. Conclusions

New fluorinated macroligands were successfully used for the dispersion ATRP of methyl methacrylate and styrene in supercritical CO_2 ($scCO_2$). Because of the dual role of the macroligands, that is, the complexation of the ATRP catalyst and the steric stabilization of growing polymer chains, well-defined polymers were formed and collected as microspheres at the end of the polymerization. The effect of the composition and molecular weight of the macroligands on the polymerization control was investigated. For the first time, living microspheres of PMMA prepared by dispersion ATRP in $scCO_2$ were used as macroinitiators for the polymerization of a fluorinated monomer (2,2,2-trifluoroethyl methacrylate), leading to the successful preparation of microspheres of a PMMA-*b*-PFMA diblock copolymer. In addition, AGET ATRP of MMA was also successfully implemented in $scCO_2$ using the same fluorinated macroligand. These achievements pave the way to the macromolecular engineering by ATRP in $scCO_2$ with the recovery of dry powders after depressurization of the reactors at high monomer conversions. Finally, polymer purification was demonstrated to be feasible by supercritical fluid extraction of the CO_2 soluble macroligand.

4. Experimental Section

4.1. Characterization. ^1H NMR spectra were recorded in $CDCl_3$ with a Bruker AN 400 spectrometer (400 MHZ) at 25 °C.

Size exclusion chromatography (SEC) was performed in THF at 45 °C with a flow rate of 1 mL/min using a SDF S5200 autosampler liquid chromatograph equipped with a SDF refractometer index detector 2000. Columns (HP PL gel 5 μm 10^5 Å, 10^4 Å, 10^3 Å, 100 Å) were calibrated with poly(methyl methacrylate) or poly(styrene) standards.

4.2. Materials. CuBr (Aldrich, 98%) was dispersed within glacial acetic acid under stirring for a few hours, filtered, washed with

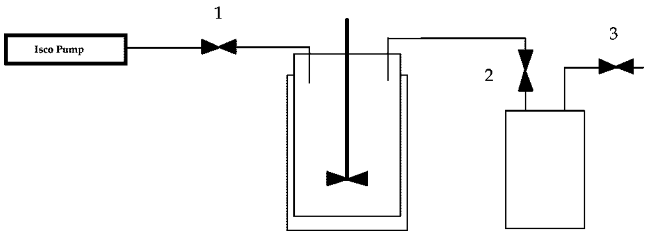


Figure 9. Experimental setup for the extraction of the catalyst.

ethanol, dried under reduced pressure at 80 °C and stored under nitrogen. Methyl methacrylate (MMA, Aldrich 99%), styrene (Aldrich, 99%), and 2,2,2-trifluoroethyl methacrylate (FMA, Aldrich, 99%) were purified by distillation under reduced pressure in order to remove the inhibitor and deoxygenated by nitrogen bubbling. Tin ethyl hexanoate (Aldrich) was used as received. Methyl α-bromophenylacetate (Aldrich, 97%) and carbon dioxide (CO_2, Air liquide, N48) were used as received.

4.3. ATRP of MMA in Supercritical Carbon Dioxide. As a typical example, the catalyst (CuBr, 0.0402 g, 2.81 10^{-4} mol) and the macroligand ($M_n = 15000$ g/mol, three TEDETA/chain, 1.22 g, 2.45×10^{-4} mol TEDETA) were introduced in a 35 mL high pressure reactor equipped with a stirring bar and oxygen was removed by CO_2 venting for 15 min. Temperature was then increased by an oil bath preheated at 70 °C. MMA (12 mL, 0.1123 mol) was introduced in a glass tube and mixed with methyl α-bromophenylacetate (0.1286 g, 5.61×10^{-4} mol) before being deoxygenated by a nitrogen purge (5 min). This mixture was injected in the preheated high pressure reactor under CO_2 flow with a glass syringe before adjusting the pressure at 320 bar. The same procedure was applied for the synthesis of PMMA by dispersion AGET ATRP and for the dispersion ATRP of styrene.

4.4. Synthesis of PMMA-Based Diblock Copolymers by ATRP in Supercritical Carbon Dioxide in a One-Pot Two-Step Process. The catalyst (CuBr, 0.0168 g, 1.17×10^{-4} mol) and the macroligand ($M_n = 15000$ g/mol, three TEDETA/chain, 0.585 g, 3.9×10^{-5} mol) were introduced in a 15 mL high pressure reactor equipped with a stirring bar and oxygen was removed by CO_2 venting for 15 min. The temperature was then increased with an oil bath preheated at 70 °C. MMA (5 mL, 0.0468 mol) was introduced in a glass tube and mixed with methyl α-bromophenylacetate (0.0536 g, 2.34×10^{-4} mol) before being deoxygenated by a nitrogen purge (5 min). The mixture was injected in the preheated high pressure reactor under CO_2 flow with a glass syringe before adjusting the pressure at 320 bar. After 24 h, a sample was picked out and analyzed by SEC chromatography and the conversion was determined by ^{1}H NMR. A total of 3 mL of deoxygenated FMA (2.1×10^{-2} mol) or MMA (0.0325 mol) were introduced under pressure in the reactor, and the pressure was adjusted at 320 bar. Stirring of the polymerization medium was maintained for 24 h before cooling and slow release of CO_2.

4.5. Extraction of the Catalyst. The experimental setup used for the extraction of the catalyst is shown in Figure 9. The venting valve of the high pressure polymerization reactor was connected to a second 50 mL high pressure cell. In a typical experiment, the extraction is conducted at constant pressure (300 bar) in the reactor by applying a back pressure with the high pressure syringe pump. The pipe that connected the two high pressure vessels was moderately heated with a heating gun in order to prevent the catalyst precipitation. CO_2 flow rate was maintained constant by finely adjusting the opening of the valve 2. CO_2 was rapidly released from the second through the venting 3. After extraction, the second reactor was opened and the extracted catalyst was collected and dried in vacuo. The pressure was finally released from the first cell, and PMMA was analyzed by ICP.

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References and Notes

(1) Barer, S. J.; Stern, K. M. *ACS Symp. Ser.* **1988**, *363*, 1–7.
(2) DeSimone, J. M.; Guan, Z.; Elsbernd, C. S. *Science* **1992**, *257*, 945–947.
(3) Guan, Z.; Elsbernd, C. S.; DeSimone, J. M. *Polym. Prepr. (Am. Chem. Soc., Div. Polym. Chem.)* **1992**, *34*, 329–330.
(4) Guan, Z.; Combes, J. R.; Elsbernd, C. S.; DeSimone, J. M. *Polym. Prepr. (Am. Chem. Soc., Div. Polym. Chem.)* **1993**, *34*, 446.
(5) Kapellen, K. K.; Mistele, C. D.; DeSimone, J. M. *Polym. Mater. Sci. Eng.* **1996**, *74*, 256–257.
(6) Sumitomo Chemical, French Patent 1,524,533, **1968**.
(7) Fukui K., Kagiya T., Yokota H., Toriuchi Y., Kuniyoshi K. U.S. Patent 3,522,228, **1970**.
(8) Hartmann H., Denzinger W. Canadian Patent 1,262,995, **1986**.
(9) Leibericht R., Dummersdorf H.-U., Waldmann H., Gasche H.-E., Kricsfalussy Z. European Patent 0,684,264 A2, **1986**.
(10) Kennedy, K. A.; Roberts, G. W.; DeSimone, J. M. *Adv. Polym. Sci.* **2005**, *175*, 329–346.
(11) Wood, C. D.; Michel, U.; Rolland, J. P.; DeSimone, J. M. *J. Fluorine Chem.* **2004**, *125* (11), 1671–1676.
(12) Michel, U.; Resnick, P.; Kipp, B.; DeSimone, J. M. *Macromolecules* **2003**, *36* (19), 7107–7113.
(13) Desimone J. M., Romack T. J. U.S. Patent 402,202, **1997**.
(14) Romack, T. J.; DeSimone, J. M.; Treat, T. A. *Macromolecules* **1995**, *28* (24), 8429–8431.
(15) Tai, H.; Wang, W.; Howdle, S. M. *Polymer* **2005**, *46* (24), 10626–10636.
(16) Tai, H.; Liu, J.; Howdle, S. M. *Eur. Pol. J.* **2005**, *41* (11), 2544–2551.
(17) Tai, H.; Wang, W.; Howdle, S. M. *Macromolecules* **2005**, *38* (5), 1542–1545.
(18) Liu, J.; Tai, H.; Howdle, S. M. *Polymer* **2005**, *46* (5), 1467–1472.
(19) Tai, H.; Wang, W.; Martin, R.; Liu, J.; Lester, E.; Licence, P.; Woods, H. M.; Howdle, S. M. *Macromolecules* **2005**, *38* (2), 355–363.
(20) Ryan, J.; Aldabbagh, F.; Zutterlund, P. B.; Okubo, M. *Polymer* **2005**, *46*, 9769–9777.
(21) Thurecht, K. J.; Gregory, A. M.; Villarroya, S.; Zhou, J.; Heise, A.; Howdle, S. M. *Chem. Commun.* **2006**, (42), 4383–4385.
(22) Yokoto, H.; Kondo, M.; Kgiya, T.; Fukui, K. *Bull. Chem. Soc. Jpn.* **1969**, *42* (5), 1412–1416.
(23) Yokoto, H.; Kondo, M.; Kgiya, T.; Fukui, K. *J. Polym. Sci., Part A: Polym. Chem.* **1968**, *1* (2), 435–446.
(24) Biddulph, R. H.; Plesch, P. H. *J. Chem. Soc.* **1960**, 3913–3920.
(25) Jessop J., Leitner W. *Chemical Synthesis Using Supercritical Fluids*; Wiley VCH: New York, 1999.
(26) Younkin, T. R.; Conner, E. F.; Henderson, J. I.; Friedrich, S. K.; Grubbs, R. H.; Bansleben, D. A. *Science* **2000**, *287* (5452), 460–462.
(27) Mecking, S.; Johnson, L. K.; Wang, L.; Brookhart, M. *J. Am. Chem. Soc.* **1998**, *120* (5), 888–899.
(28) Loeker, F. C.; Duxbury, C. J.; Kumar, R.; Gao, W.; Gross, R. A.; Howdle, S. M. *Macromolecules* **2004**, *37* (7), 2450–2453.
(29) Stassin, F.; Halleux, O.; Jerome, R. *Macromolecules* **2001**, *34* (4), 775–781.
(30) Stassin, F.; Jerome, R. *Chem. Commun.* **2003**, *2*, 232–233.
(31) Stassin, F.; Jerome, R. *Macromol. Symp.* **2004**, 135–146.
(32) Thurecht, K. J.; Heise, A.; deGeus, M.; Villarroya, S.; Zhou, J.; Wyatt, M. F.; Howdle, S. *Macromolecules* **2006**, *39* (23), 7967–7972.
(33) Villarroya, S.; Zhou, J.; Thurecht, K. J.; Howdle, S. M. *Polym. Prepr. (Am. Chem. Soc., Div. Polym. Chem.)* **2006**, *47* (2), 231–232.
(34) Guan, Z.; Combes, J. R.; Elsbernd, C. S.; DeSimone, J. M. *Polym. Prepr. (Am. Chem. Soc., Div. Polym. Chem.)* **1993**, *34* (1), 447–448.
(35) Ehrlich, P. *Chemtracts: Org. Chem.* **1993**, *6*, 92.
(36) DeSimone J. M. U.S. Patent 5,496,901, **1996**.
(37) DeSimone J. M. U.S. Patent 5,688,879, **1997**.
(38) DeSimone J. M. U.S. Patent 5,739,223, **1998**.
(39) Cooper, A. I. *J. Mater. Chem.* **2000**, *10*, 207, and references herein.
(40) Woods, H. M.; Silva, M. C. G. C.; Nouvel, C.; Shakesheff, K. M.; Howdle, S. M. *J. Mater. Chem.* **2004**, *14* (11), 1663, and references herein.
(41) Kendall, J. L.; Canelas, D. A.; Young, J. L.; DeSimone, J. M. *Chem. Rev.* **1999**, *99* (2), 543–563.
(42) Xia, J.; Johnson, T.; Gaynor, S. G.; Matyjaszewski, K.; DeSimone, J. M. *Macromolecules* **1999**, *32* (15), 4802.

(43) Minami, H.; Kagawa, Y.; Kuwahara, S.; Fujii, S.; Okubo, M. *Des. Monomers Polym.* **2004**, *7* (6), 553–562.

(44) Villarroya, S.; Zhou, J.; Duxbury, C. J.; Heise, A.; Howdle, S. M. *Macromolecules* **2006**, *39* (2), 633–640.

(45) Duxbury, C. J.; Wang, W.; deGeus, M.; Heise, A.; Howdle, S. M. *J. Am. Chem. Soc.* **2005**, *127*, 2384–2385.

(46) Villarroya, S.; Zhou, J.; Duxbury, C. J.; Howdle, S. M. *Macromolecules* **2006**, *39* (26), 9080–9086.

(47) Zhou, J.; Villarroya, S.; Wang, W.; Wyatt, M.; Duxbury, C. J.; Thurecht, K. J.; Howdle, S. M. *Macromolecules* **2006**, *39* (16), 5352–5358.

(48) Thurecht, K. J.; Gregory, A. M.; Wang, W.; Howdle, S. M. *Macromolecules* **2007**, *40* (9), 2965–2967.

(49) Grignard, B.; Jerome, C.; Calberg, C.; Jerome, R.; Detrembleur, C. *Eur. Polym. J.* **2008**, *44* (3), 861–871.

(50) Grignard, B.; Jerome, C.; Calberg, C.; Jerome, R.; Wang, W.; Howdle, S. M.; Detrembleur, C. *Chem. Commun.* **2008**, *3*, 314–316.

(51) McHugh, M. A.; Rindfleisch, F.; Kuntz, P. T.; Schamltz, C.; Buback, M. *Polymer* **1998**, *39* (24), 6049–6052.

(52) Lora, M.; McHugh, M. A. *Fluid Phase Equilib.* **1999**, *157* (2), 285–297.

(53) Byun, H.-S.; Choi, T.-H. *J. Appl. Polym. Sci.* **2002**, *86* (2), 372–380.

(54) Byun, H.-S.; Kim, J.-G.-S.; Yang, J. *IEC Res.* **2004**, *43* (6), 1543–1552.

(55) Kleij, A. W.; Gossage, R. A.; Gebbink, R. J. M. Klein; Brinkmann, N.; Reijerse, J.; Kragl, U.; Lutz, M.; Spek, A. L.; van Koten, G. *J. Am. Chem. Soc.* **2000**, *122* (49), 12112–12124.

(56) DeSimone, J. M.; Maury, E. E.; Menceloglu, Y. Z.; McLain, J. B.; Romack, T. J.; Combes, J. R. *Science* **1994**, *265* (5170), 356–359.

(57) Hsiao, Y.-L.; Maury, E. E.; DeSimone, J. M.; Mawson, S.; Johnston, K. P. *Macromolecules* **1995**, *28* (24), 8159.

(58) Hsiao, Y.-L.; DeSimone, J. M. *J. Polym. Sci., Part A: Polym. Chem.* **1997**, *35* (10), 2009–2013.

(59) Canelas, D. A.; Betts, D. E.; DeSimone, J. M.; Yates, M. Z.; Johnson, K. P. *Macromolecules* **1998**, *31* (20), 6794–6805.

(60) Sihoh, H.; DeSimone, J. M. *J. Polym. Sci., Part A: Polym. Chem.* **1999**, *37* (14), 2429–2437.

(61) Schaffer, K. A.; Jones, T. A.; Canelas, D. A.; DeSimone, J. M. *Macromolecules* **1996**, *29* (7), 2704–2706.

(62) Woods, H. M.; Nouvel, C.; Licence, P.; Irvine, D. J.; Howdle, S. M. *Macromolecules* **2005**, *38* (8), 3271–3282.

(63) Wang, W.; Naylor, A.; Howdle, S. M. *Macromolecules* **2003**, *36* (14), 5424–5427.

(64) Giles, M. R.; O'Connor, S. J.; Hay, J. N.; Winder, R. J.; Howdle, S. M. *Macromolecules* **2000**, *33* (6), 1996–1999.

(65) Christian, P.; Howdle, S. M.; Irvine, D. J. *Macromolecules* **2000**, *33* (2), 237–239.

(66) Alessi, P.; Cortesi, A.; Kikic, I.; Vecchione, F. *J. Appl. Polym. Sci.* **2003**, *88* (9), 2189–2193.

(67) Jakubowski, W.; Matyjaszewski, K. *Macromolecules* **2005**, *38* (10), 4139–4146.

(68) Mert, H.; Tunca, U.; Hizal, G. *J. Polym. Sci., Part A: Polym. Chem.* **2006**, *44* (20), 5923–5932.

(69) Tang, H.; Radosz, M.; Shen, Y. *Macromol. Rapid Commun.* **2006**, *27* (14), 1127–1131.

(70) Min, K.; Jakubowski, W.; Matyjaszewski, K. *Macromol. Rapid Commun.* **2006**, *27* (8), 594–598.

(71) Bratton, D.; Brown, M.; Howdle, S. M. *Macromolecules* **2005**, *38* (4), 1190–1995.

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