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A review on
Controlled radical polymerization and Atom Transfer Radical Polymerization

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Abstarct: Synthesis of polymers with predicted molecular weight, narrow MWD and chain end functionality is prime requisite in these days. Atom transfer radical polymerization (ATRP) is an effective technique for the design and preparation of multifunctional, nanostructure materials for a variety of application in biology and medicine.

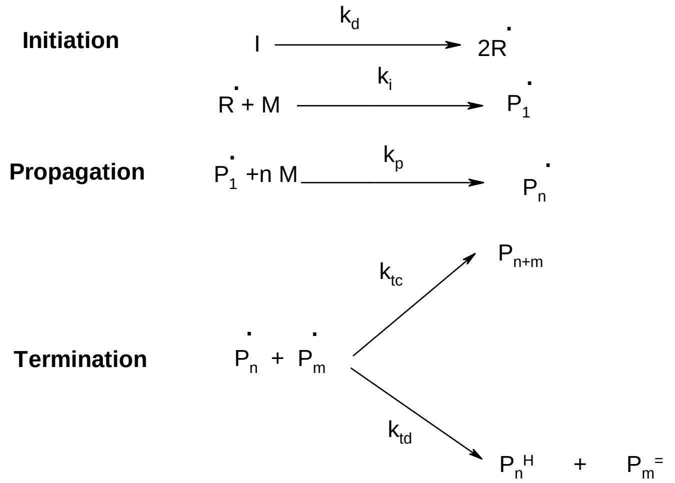
Key words: Controlled radical polymerization, Kinetics, ATRP, star and block copolymer

1.1 INTRODUCTION

In recent years, the rapid growth of electronic and medical technologies has led to an understanding of the individual polymeric molecule and thus enables us to tailor them suitably to exhibit desirable properties. These properties are, in turn, governed by the molecular properties such as molecular weight, MWD and topology. These parameters can be more precisely controlled in polymers prepared using living or controlled polymerization method. Using these methods it is possible to synthesize polymers with predicted molecular weight, narrow MWD and chain end functionality besides preparing polymers with a variety of architectures. It was Szwarc and coworkers who first demonstrated the living polymerization of styrene and obtained polystyrene with narrow MWD[1] via the living anionic polymerization technique. This anionic polymerization technique is good for the synthesis of well-defined functional homo-polymers and block, graft and star copolymers. Several other methodologies were developed to attain control over polymerization and these include cationic, group transfer, metathesis and coordinated polymerizations. More recently a new methodology, atom transfer radical polymerization (ATRP), has been successfully developed for making polymers with controlled molecular weight, molecular weight distribution. The advantages of the ATRP over conventional living polymerization methods are: it is more tolerant towards protic and other impurities; it can be used for a wide range of monomers and can be used in bulk, solution, dispersion and emulsion.

1.2 Free Radical Polymerization

Free radical polymerization is the most widely used method of polymerization of vinylic monomers[1]. It includes three basic steps initiation, propagation and termination[2,3](Scheme 1.1).



Scheme 1.1: *Mechanism of a free radical polymerization*

The three basic mechanistic steps in a free radical polymerization are initiation, propagation and termination. Initiation consists of the slow decomposition of initiator, I to give two radical species with a rate constant of k_d. They quickly add to a monomer, M to form chain initiating radicals. During propagation, the later successively add to monomer units with a rate constant k_p and the polymer chains grow until termination occurs. Termination is the reaction of two radicals either by combination (k_{tc}) or by disproportionation (k_{td}). Combination occurs when two radicals couple together to form a longer dead chain. Disproportionation is the result of the abstraction of a β-hydrogen from one radical chain by another to form a polymer chain with saturated and an unsaturated end group.

It is to be noted that often a chain transfer reaction occurs where hydrogen or other species is transferred from a component of the reaction mixture, e.g. monomer, initiator or solvent to the growing radical. A new radical is generated which can reinitiate polymerization. The direct consequence of chain transfer is the production of low molecular weight polymer.

Advantages of the free radical polymerizations are: (i) it is compatible with many monomers including functional monomers; (ii) versatile with regard to reaction conditions and (iii) widely applied in the industry for the above reasons. The clear limitations are: (i) due to diffusion–controlled termination reactions between growing radicals, there is a poor control over molar mass distribution (MMD), (ii) since, the typical life time of a propagating chain is very short (typically less than a second or, at most few seconds), it is not possible to synthesize block copolymers or other chain topologies and (iii) there is no control over chain tacticity.

In order to retain the advantages of conventional free radical polymerization (FRP) and minimize its disadvantages controlled radical polymerization (CRP) techniques were developed. The main similarity between CRP and FRP is the participation of free radicals in the chain growth. The main difference between CRP and FRP is that, in CRP, the steady concentration of free radicals is established by balancing rates of activation and deactivation, but in FRP this is realized by balancing the rates of initiation and termination.

1.3 Controlled Radical Polymerization (CRP)

Over the past few decades, controlled/living polymerization methodology has steadily expanded to include all of the chain-growth polymerization methods: cationic, anionic, transition metal catalyzed and most recently, free radical polymerizations. The limited commercial application of living ionic polymerization stems from the need for high purity solvents and reagents, low reaction temperatures and solvents that do not induce chain transfer. Another important disadvantage of living ionic polymerization is that it can only exploit a limited variety of monomers. This makes CRP extremely important from commercial point of view, which combines the benefits of a living system with the versatility of a radical process.

In the true sense, the controlled radical polymerization is a chain-growth polymerization that proceeds in the absence of irreversible chain-termination and chain-transfer steps. Thus, once a chain is initiated, it will grow until all the monomer is consumed, in which case chain growth will resume. In such cases, initiation is complete and exchange between species of various reactivity is fast, the final average molecular weight of the polymer can be adjusted by varying the initial conditions ($DP=\Delta[\text{Monomer}]/[\text{Initiator}]_0$, where DP=degree of polymerization) while maintaining a narrow molecular weight distribution ($1.5<M_w/M_n\approx1.0$, where M_w=weight-average molecular weight and M_n=number average molecular weight).

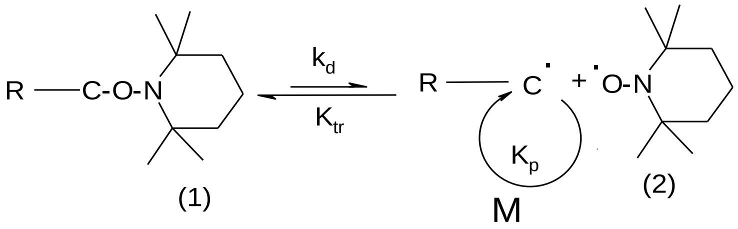
In 1956 Szwarc et al[1]. reported the first observation of polymerization that had living characteristics. He demonstrated that the rate of termination for the polymerization of styrene using sodium naphthalene in the absence of impurities was absent. Furthermore, chain transfer activity was suppressed by the use of highly purified, dry aprotic reagents and so 100% conversion of styrene to polystyrene was achieved. It was concluded that the lack of chain termination and chain transfer events was due to the charge repulsion between chain ends. Although, anionic polymerization gave polymers with controlled molecular weight with narrow PDI, however it has limitation such as: (i) high purity of monomer, solvent etc, (ii) limited monomer i.e. monomers having electron withdrawing groups can be polymerized. Due to these limitations, such methods lack its commercial use and researchers were looking for an alternative route to prepare polymers wit controlled molecular weight and molecular weight distribution with controlled architecture. Controlled free radical polymerization is gainig importance in the field of polymer science which is discussed in the following text.

1.3.1 Types of Controlled Radical Polymerization:

There are four different types of controlled radical polymerization methodologies known so far. These are (1) nitroxide mediated stable free radical polymerization (SFRP or NMP)[4-6], (2) reversible addition fragmentation chain transfer reaction (RAFT)[7, 8], (3) atom transfer radical polymerization (ATRP)[9, 10] and (4) degenerative chain transfer (DT)[11, 12]. An outline of each of these is provided in the following pages.

(i) Nitroxide Mediated Stable Free Radical Polymerization (SFRP or NMP)

Solomon et al.[13] discovered and patented the Nitroxide-Mediated Controlled Radical Polymerization in 1985. It is based on the reversible deactivation or 'trapping' of growing polymer radicals by a stable free nitroxide radical. The reversible deactivation equilibrium in nitroxide mediated CRP is depicted in scheme 1.2. As the trapping reaction of the stable nitroxide redical (2) with the growing polymer radical is near diffusion controlled, the equilibrium is strongly shifted towards the dormant side (1). This ensures a low concentration of reactive radicals resulting in suppression of termination events relative to propagation events.[14, 15]



Scheme1.2: *Reversible deactivation equilibrium in nitroxide mediated CRP*

Table1.1: Types of monomer polymerized by Nitroxide mediated method

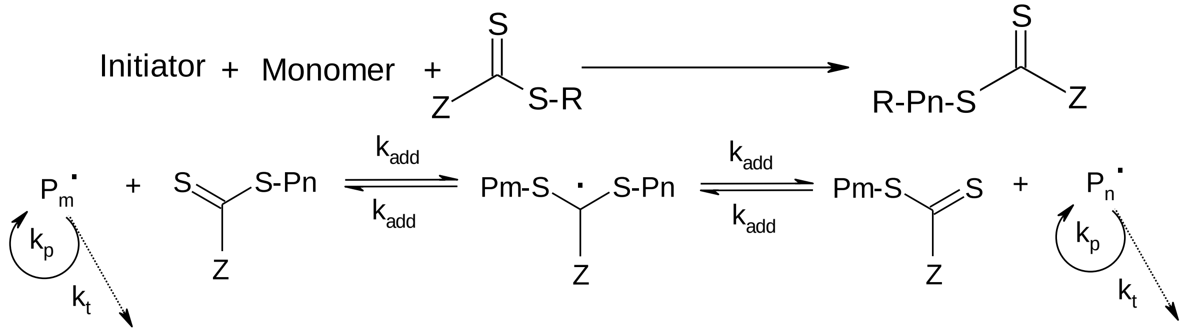
Monomer	Type of Nitroxide initiator	Reference
Styrene 4-vinylpyridine	2,2',6,6'-tetramethyl-1-piperidinyloxy(TEMPO)	16, 17
Styrene Acrylate Acrylamide Acrylnitrile	2,2,5-trimethyl-4-phenyl-3-azahexane 3-oxy derivative	18
Isoprene 1,3 butadiene	2,2,5-trimethyl-4-phenyl-3-azahexane 3-oxy derivative	19
Acrylic acid	N-tert-butyl-N-(1-diethyl phosphono-2,2dimethyl propyl)) Nitroxide	18

(ii) Reversible Addition-Fragmentation Chain Transfer (RAFT)

This is relatively a new technique reported by Rizzardo et al.[7, 8] in 1998. Simple organic compound possessing the thiocarbonylthio moiety were effective in controlling the polymerization by reversible addition-fragamention chain transfer process. There are four classes of thiocarbonylthio RAFT agents, depending on the nature of the activating (Z) group: (i) dithioesters (Z = aryl or alkyl), (ii) trithiocarbonates (Z = substituted sulfur), (iii) dithiocarbonates (xanthates), and (iv) dithiocarbamates (Z = substituted nitrogen).[20]

In a RAFT mechanism, initiation occurs via the decomposition of free radical initiator leading to formation of propagating chains. This is followed by addition of the propagating radical, giving rise to a polymeric RAFT agent and a new radical.

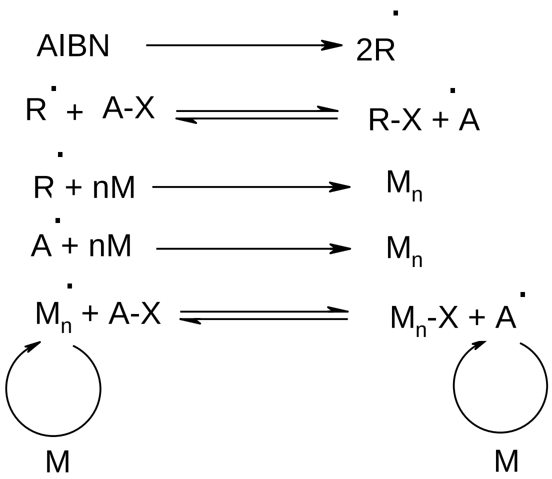
This radical reinitiates the polymerization to form new propagating radicals. The RAFT process relies on this rapid central addition fragmentation equilibrium between propagating and intermediate radicals and chain activity and dormancy as shown in scheme 1.3. Many novel complex structures can be prepared using RAFT polymerization including blocks, gradients, stars and combs.[21, 22]



Scheme1.3: *The central RAFT equilibrium*

(iii) Degenerative Chain Transfer (DT)

Another route for achieving living free radical polymerization involves degenerative chain transfer.[11, 12] A simplified mechanisms for this process is shown in scheme 1.4.



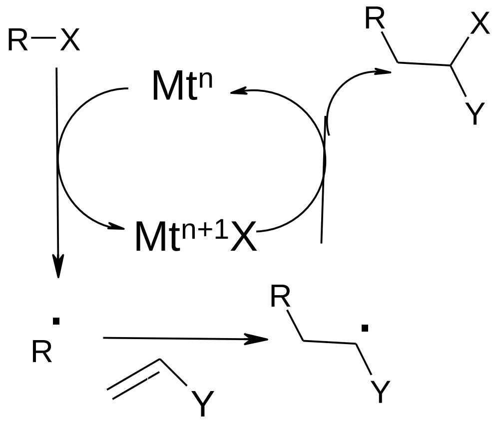
Scheme1.4: *Simplified Mechanism of Degenerative Chain Transfer*

Where $R^{\cdot}$ is an initiator radical generated from the thermal decomposition of a conventional free radical initiator such as 2,2'azobisisobutyronitrile (AIBN), A-X is the transfer agent ($A^{\cdot}$= an organic radical moiety e.g., $PhC^{\cdot}H_2$, $Ph(CH_3)C^{\cdot}$,$(CH_3)_2C^{\cdot}COOEt$ etc. and X= iodine atom. The radicals present at certain low concentration, of formed continuously during slow initiation, add to monomer and react with the transfer agent (A-X) reforming the growing radicals.

The main requirement for achieving living character is that an initiator radical ($R^{\cdot}$) or growing radical ($R\text{-}M_n^{\cdot}$) reacts rapidly and selectively with a transfer agent A-X to exchange X and form dormant species R-X or $R\text{-}M_n\text{-}X$ and a new radical $A^{\cdot}$ capable of chain growth. The later after addition of monomer until will react with the transfer agent R-X or $R\text{-}M_n\text{-}X$. If this exchange is fast relative to propagation of radicals, polymers with narrow molecular weight distribution can be obtained.

(iv) Atom Transfer Radical Polymerization (ATRP)

Transition metal mediated atom transfer addition (ATRA) or Kharasch addition[23] reactions are well known in the literature.[24-26] These reactions proceed by the transfer of an atom or molecule from substrate to a transition metal complex generating radical intermediates. These radicals participate in further reaction by intra- or inter –molecular addition to unsaturated group to form a transient product radical to which the halide is transferred back. If the starting and product radicals are of similar reactivity it is possible to repeat the catalytic cycle for multiple additions of unsaturated monomers leading to a polymerization reaction.



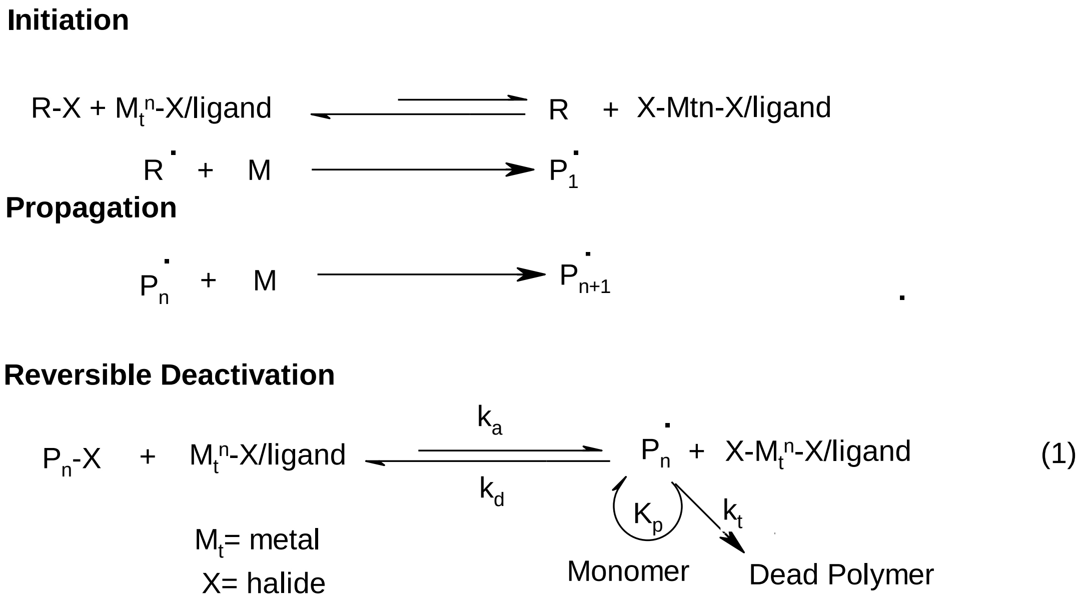
Scheme1.5: *General mechanism of atom transfer radical addition (ATRA)*

Copper[28] and other transition metal with a d^n electronic structure such as nickel[29], palladium[30], rutheniaum[30] and iron[31] have been used in the ATRA.

The mechanism is believed to proceed via an inner–sphere electron transfer, which reversibly generates the radical ($R^{\cdot}$) and the oxidized metal complex (M_t^{n+1}). The radical that is formed after the addition of the alkenes is generally much less stabilized than that radical that exist before. The subsequent reaction of the newly formed radical with M_t^{n+1} is therefore irreversible and explains why only one alkene addition can take place in ATRA. It is assumed that the intermediate species are free radicals and that neither solvent-cage effects, nor coordination with the metal centre occurs. The metal complex abstracts the halogen (X) from the initiator and a radical is formed. It then adds to monomer M and further propagates by the addition of monomer, at some stage during propagation the propagating species abstract a halogen from the oxidized metal complex X- M_t^{n+1}-X/Ligand to form a dormant species.

1.4 General Mechanism of ATRP

This is a one electron process and the lower oxidation state catalyst M_t^n-X/ligand is regenerated in the process. Equilibrium is set up between active and dormant species referred to as the reversible termination step (1) in scheme 1.6.



Scheme1.6: *Mechanistic representation of ATRP*

The dormant species is favored in the equilibrium so that the concentration of active species is always low which renders bimolecular termination negligible. The equilibrium constant ($K_{eq}=K_a/K_d$) must not be too low. This will result in very slow polymerization rates. The component reaction at equilibrium should be fast that all the chains have equal probability of growing to the same extent leading to narrow PDI.

The radical mechanism proposed has been tested by comparison with some typical features of free radical polymerizations. The use of scavenger such as galvinoxyl compounds have been shown to inihibit polymerization for a number of different metal complexes.[9, 32-34] The stereochemistry of PMMA polymers obtained was also very similar to that obtained using conventional radical polymerizations, strongly suggesting that the propagating species are radicals. Measured reactivity ratios for the monomer pair MMA and n-butyl methacryalte (n-BMA) [33, 34] also compared well with values obtained from classical free radical polymerizations.[32] However, the evidence is not entirely conclusive of a radical propagating species. This is the possibility that the radical formed through halogen transfer to the metal centre is confined to the coordination sphere of the complex in its oxidized state and propagating from this species and not a 'free' radical.

1.5 Requirements of ATRP

In CRP or ATRP, a good control system produces polymer with low PDI (~1.3) and the number average molecular weight should be close to the theoretically predicted value. Also the molecular weight should increase linearly with monomer conversion. A controlled system also generally shows linear ln $[M]_0/[M]$ vs t plot and narrow molecular weight distribution depend on how far the following requirements are met with.

(1) The dynamic equilibrium between dormant species and the corresponding radicals should be overwhelmingly lie towards the dormant species side i.e. the concentration of radicals at any time t should be very small and steady. For this to happen, the metal complex at its higher oxidation state must deactivate the radical at a rate which must be overwhelmingly larger than that of the termination.

(2) Both the activation and deactivation rate constants should be very high but the rate constant for deactivation must be higher than the rate constant for activation i.e., $k_d >> k_a$. If ka is higher than kd or both ka and kd are small then polymers with relatively higher molecular weight and broad PDI are obtained.

(3) The propagation rate should be less than that of deactivation and activation. If growing radicals propagate with a much higher rate than the deactivation of polymer radicals and activation of dormant species, then all the molecules will not grow at the same rate and therefore less control on molecular weight and broad molecular weight distribution occurs.

(4) The reactivity of alkyl halide initiator in terms of activation and propagation should be similar to that of the polymeric alkyl halide formed by the deactivation of growing polymeric radicals by the deactivator. For example, in the ATRP of styrene, 1-phenylethylbromide acts as a very successful initiator[35].

1.6 Components of Atom Transfer Radical Polymerization

To obtain well- defined polymers, a number of factors need to be considered. The importance of various components and conditions of reactions are discussed below:

(i) Monomers

Various monomers such as styrene, substituted styrene[36, 37], (meth) acrylates[38], methacrylamide[39], dienes[40], acrylonitrile[41] etc. have been successfully polymerized using ATRP. Each monomer has its own equilibrium constant. ($K_{eq}=K_a/K_d$) for active and dormant species in ATRP even with the same catalyst and conditions. The product of kp and keq determines the polymerization rate. Thus, the polymerization will occur very slowly if K_{eq} is too small. This could be the plausible reason why polymerization of less reactive monomers like olefins, halogenated alkenes and vinyl acetate are not yet successful[42]. Because of this reason, optimal conditions for ATRP such as the catalyst type, ligand, solvent, temperature and additives are to be chosen for each monomer.

Styrene and its derivatives were polymerized using ATRP with copper [36, 43], ruthenium[44], iron[46] catalyst system to a molecular weight range of 1000-100,000 gmole^{-1}. Among them, the polymerization using CuBr/ dNbpy as the catalyst ligand complex and alkyl bromides as initiator at 110˚C has been extensively studied. When chloride was replaced in place of bromide, similar polymerization rates were obtained at 130˚C.[36] Good control was obtained even at 80-90˚C in a reasonable time when a more efficient CuBr/PPMI or copper acetate CuOAC/CuBr/dNbpy catalyst system were used.[47] However, to maintain a sufficiently large propagation rate, to increase the solubility of the catalyst complex and to avoid vitrification at high conversions, higher reaction temperature (>100˚C) are required for styrene. But better control is obtained at lower temperatures, presumably due to a lower contribution of the thermal self-initiation.[48, 49] The polymerization can be carried out in bulk or in solution, but as the stability of the halide end group depends on solvent,[50] non-polar solvents are preferred. A wide range of styrene derivatives were polymerized by ATRP in a controlled fashion and observed that the styrene with electron withdrawing groups polymerized faster.[37]

ATRP of MMA has been reported with copper[38, 51], ruthenium[9, 52], nickel[33], iron[46] palladium[39] and rhodium [30] catalyst complexes. The facile polymerizability and the large range of available catalysts for the ATRP of MMA are due to the relative ease of activation of the dormant species and the high values of K_{eq}. K_{eq} values are too high, when [2(dimethyl amino) ethyl] amine) Me$_6$TREN was used as ligand, to obtain a controlled polymerization. Most polymerization reaction were carried out at 70-90˚C. Solvent is necessary to solubilize the forming PMMA and to keep the growing radical concentration low. Under comparable conditions MMA has a significantly higher K_{eq} than styrene and methacrylate, necessitating higher dilution and lower catalyst concentration.[42]

Initiator plays an important role in ATRP of MMA. Best initiator of MMA includes sulfonyl chlorides[51] and 2-halopropionitrile [46] due to their sufficiently large apparent rate of initiation. Other methacrylic esters such as n-butyl methacrylate,[54, 55] 2-(dimethylamino)ethyl methacrylate,[56] 2-hydroxyethyl methacrylate (HEMA),[57] methacrylic acid in its alkyl protected form[58], fluorinated methacrylic esters[59] and methacrylates with oligo(ethylene oxide)[60] substituents were successfully polymerized using ATRP. Other monomers polymerized by ATRP include acrylonitrile[61], (meth)acrylamides [62, 63] and 4-vinylpyridine.[64]. Acidic monomers fail to polymerize because they can protonate ligands and form the corresponding carboxylate salts. Armes et al.[56, 50] recently reported the direct atom transfer radical polymerization of salts of acidic monomers in presence of less basic oxygen and sulphur-based ligand. Halogenated alkens, alkyl-substituted olefins and vinyl esters are presently resistant to polymerization by ATRP due to very low intrinsic reactivity in radical polymerization and radical addition reactions and could have a very low ATRP equilibrium constant.

The effect of monomer structure has been studied by Qie et al.[37] and studied polymerization with a series of substituted styrene. Monomers having electron withdrawing substituent polymerize faster and gave better control of molecular weight distribution than monomer with electron donating substituent. The authors explain the differences by stating that the equilibrium electron-withdrawing substituent increases the propagation rate constant as well as the equilibrium constant. These substituent therefore increases the monomer reactivity (higher k_p) and lower the stability of the dormant species.

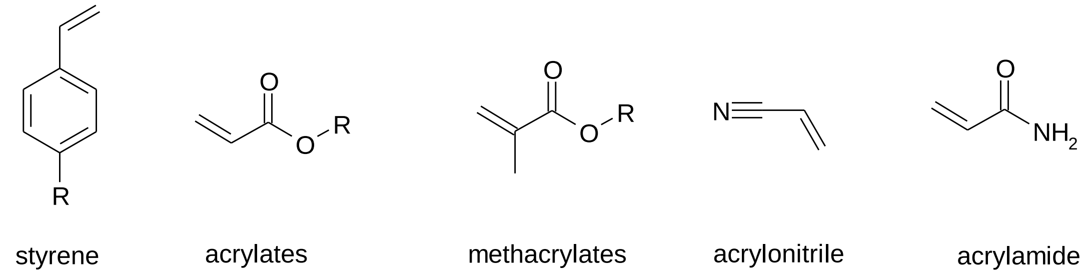
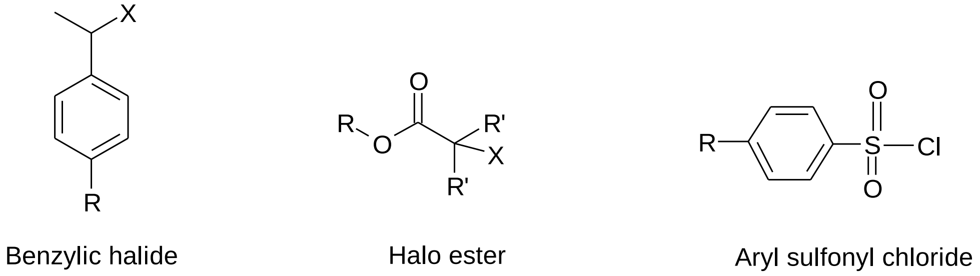


Figure1.1: *Different monomers polymerizable by ATRP*

(ii) Initiators

The main role of the initiator (R-X) in metal catalyzed living radical polymerization is to form an initiating radical species via homolytic cleavage of its labile bond such as C-halogen by the metal catalysts. Usually, alkyl halides are used as initiator in ATRP. For successful control of molecular weight and molecular weight distribution, the initiator needs to fulfill two important requirements. First, the initiator should quantitatively generate chains, i.e. upon dissociation all radicals should lead to the formation of a dormant species. Recombination of initiator–derived radicals would lead to higher molecular weight than was targeted for and is therefore unfavorable. Second, the dissociation of the alkyl halide should be fast in comparison to the propagation. If this is not the case, this leads to broadening of the molecular weight distribution. The dissociation energy of the carbon-halide bond of the initiator should therefore be sufficiently low to facilitate a rapid transfer of the halide radical from the alkyl halide to the transition metal species. The initiator is thus chosen so that the initiation occurs fast and is quantitative, with the dormant polymer chain end being stable during the polymerization. This means that the initiator should be carefully selected in accordance with the structure and reactivity of the monomers and metal complexes. Organic halides with a potentially active carbon-halogen bond are mostly employed as initiator.[42]. Alkyl bromides and chlorides are most successful in ATRP. The structure of the alkyl part is also of importance. Usually the alkyl part of the initiator should have structure resemblance to that of the monomer involved in polymerization. For polymerization of styrene 1-phenylethylbromide can be used in polymerization, while for the polymerizations of methyl methacrylate ethyl-2- bromoisobutyrate is suitable. Arylsulfonyl chlorides are an efficient and universal series of initiator for the metal catalyzed living radical polymerizations of various monomers.[43, 65]. These arylsulfonyl chlorides dissociate homolytically between the sulphur and the chlorine atom and yield highly reactive sulfonyl radicals. This leads to much faster initiation than in the case when e.g. ethyl -2-bromoisobutyrate is used.

On the other hand, when using arylsulfonyl chlorides, more bimolecular termination takes place in the beginning of the reaction due to the high radical flux, although it must be noted that primary radicals derived from aryl sulfonyl chlorides can only recombine after addition of at least one monomer unit.



X = halogen (Cl, Br)
R = alkyl
R' = H, alkyl or halogen

Figure1.2: *Typical alkyl halide initiators used in ATRP*

Halonitriles are specifically employed for the polymerization of aryl nitrile with copper halides. The strong electron – withdrawing cyano group facilitates the formation of initiating radicals [42].

(iii) Catalysts

Catalyst is most important component of ATRP for determining the position of equilibrium dynamics between active and dormant species. Mostly used catalysts in ATRP are transition metal catalysts based on copper[32, 36, 38, 54, 66-69], nickel,[33] iron[40, 57] and ruthenium.[9] The prerequisites for an efficient catalyst are:

(1) Two readily available oxidation states separated by one electron.
(2) Reasonable affinity towards a halogen atom.
(3) Relatively strong complexation with ligand and
(4) An expandable coordination sphere to accommodate a (pseudo) halogen.

Copper mediated ATRP have been extensively studied with halides as counter ions. Styrene, methyl acrylate and MMA were polymerized successfully with a linear increase in molecular weight and fairly narrow PDI (< 1.5) using cuprous halides complexed with bipyridyl ligands.[70] Based on experimental data it was proved that the polymerization using the catalyst systems proceed via radical pathway.[71] Polymerization was tolerant to a variety of functional groups such as alcohols and amines and insensitive to additives such as water, methanol and acetonitrile.[36] Counterions other than halides, such as, carboxylates,[47] hexaflouro phosphate,[73] triflate [37] and CuY (Y = O, S, Se, Te)[72] have also been used in copper mediated ATRP. The polymerization rate increased with copper acetate at the expence of control, but better control was achieved in this system by adding small amount of Cu(I) or Cu(II) halide, while maintaining the fast polymerization rate.[73]

(iv) Ligands

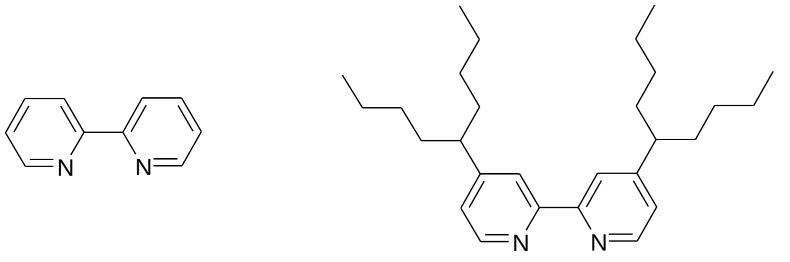
Ligands play a crucial role in ATRP by controlling the solubility of the complex in the reaction mixture and ensure stability of the complex in different monomers, solvents and the temperatures. It adjusts the redox potential around the metal center, thus affecting the reactivity and equilibrium dynamics of the atom transfer process. They can fine tune the selectivities and force the complex to participate in a one-electron transfer process needed for ATRP. The ligands can also facilitate the removal and recycling of the catalyst allowing the immobilization of catalyst.

Various ligands based on nitrogen and phosphorus have been used in ATRP. Nitrogen based ligands have been particularly successful in copper and iron mediated ATRP whereas phosphorus, sulfur, oxygen based ligands have been less effective. The electronic and steric effects of the ligands are important. Catalytic activity is reduced when there is excessive steric hindrance around the metal center and also when the ligand used had strongly electron withdrawing substituents. It was also observed that the activity of N-based ligands in ATRP deceases with the number of coordinating sites i.e. $N_4 > N_3 > N_2 >> N_1$ and with the increasing number of linking C-atoms i.e. $C_2 > C_3 >> C_4$. Activity is usually higher for bridged and cyclic system than for linear analogues. Another important consideration in choosing the ligand is the possible side reactions such as the reaction of amines (especially aliphatic) and phosphines with alkyl halides. These side reactions are reduced when tertiary amines are used as ligands and minimum when the ligands are complexed to CuBr.

Phosphorus ligands have been used in ATRP in conjunction with most transition metals such as ruthenium[49], rhodium[63, 34], nickel[74], iron[46] and palladium[53]. Amongst the phosphorus based ligands (mostly PR_3 type), phosphines display a high catalytic activity and good control of the polymerization. Recently, cyclopentadienyl, indenyl and 4-isopropyl toluene type ligands were used in ruthenium based ATRP and these ligands results in more reactive catalysts than the ones obtained with phosphorus[52, 75, 76]. Oxygen based ligands such as phenol and carboxylic acids have also been considered as ligands in ATRP[47, 77].

Bipyridine Type Ligands

Bipyridine was the first ligand to be used in conjunction with CuCl in CRP by Matyjszewski[10]. This ligand soon after was used by Percec and co-workers[43] to demonstrate the use of arylsulfonyl chlorides as efficient initiators. The bpy complexes are however not fully soluble in the reaction media. More soluble bpy based ligands have subsequently been investigated. Matyjszewski reported polydispersities as small as 1.03 for the polymerization of styrene and methyl acrylate[78, 79]. The use of 4,4'-dinonyl, 2, 2'-bipy reduced the polydispersity of polystyrene from greater than 1.4 for unsubstituted bipy to 1.3 using aryl sulfonyl chloride initiators[80].



2,2'- bipyridine (bpy)   4,4'-di(5-dinonyl)2,2'- bipyridine (dNbpy)

Figure1.3: *Ligands based on bipyridine*

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Alkylpyridinemethanimine Type Ligands

Alkylpyridinemethanimine ligands were proposed by Haddleton[38]. The synthesis of these ligands is relatively simple and involves the condensation of pyridine 2-carboxaldehyde with suitable alkyl amine. A variety of ligands can be obtained by simply changing the alkyl group on the amine.

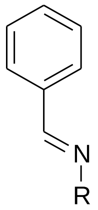
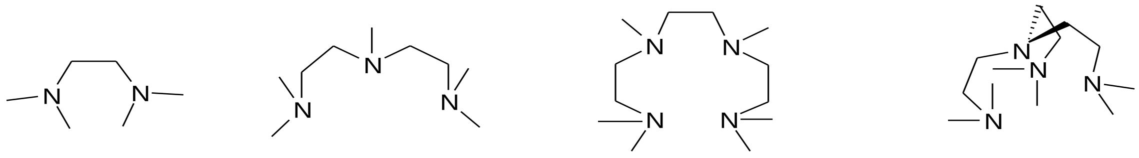


Figure1.4: *N-Alkyl-2-pyridinemethanimine type ligand for ATRP*

This ligand has been successful for the polymerization of higher alkyl methacrylates[38]. The crystal structure of an isolated copper complex with N-(t-butyl)-2-pyridinemethanimine showed a tetrahedral copper centre[81]. However, active catalyst during polymerization may be of a different structure. A variety of R groups were investigated and it was found that linear alkyl groups gave faster and better controlled polymerizations. The n-propyl, n-butyl, n-pentyl, n-hexyl and n-octyl ligands all gave similar rates for the polymerization of MMA. The shorter alkyl chain ligands form heterogeneous reaction mixtures both at room temperatures and polymerization temperatures. Perrier used the n-pentyl ligand to polymerize styrene at 110˚C[82]. Lauryl methacrylate was polymerized in controlled way in the presence of EBiB/ CuBr/*N*-(-n propyl-2 pyridinemethanimine) (PPMI) however, they used a very dilute solution of monomer (15% by volume) [83]. Bulk polymerization of stearyl acrylate (ODA) by ATRP (CuBr/PPMI) at 95˚C was reported by Street et.al[84].

Multidentate Linear Amine ligands.

Matyjszewski[44] reported the use of multidentate linear amine ligands having the structure given in Figure 1.5.



Tetramethyl ethylene diamine (TMEDA)

N,N,N',N'',N'' pentamethyl diethylene triamine (PMDETA)

1,1,4,7,10,10 hexamethyl triethylene tetramine (HMTETA)

Tris [2 (dimethylamino)ethyl] amine(Me6TREN)

Figure1.5: *Structure of different multidentate amine ligands*

Tetramethylethylenediamine (TMEDA), pentamethyldiethylenetriamine (PMDETA) and hexamethyltriethylenetetraamine (HMTETA) are commercially available and cheaper than bpy. They were successfully used for the CRP of MMA, MA and styrene[112]. TMEDA and HMTETA were more successful. They gave faster polymerization of MA and styrene than bpy and its derivative and similar polydispersities. The rates of polymerization of styrene using both ligands were very similar. The optimum ratio of copper (I) to ligand was 1:1 for the tridentate PMDETA and quadridentate HMTETA. Another quadridentate ligand Me$_6$TREN was prepared from commercially available TREN and was found to give extremely fast polymerization of MA and n-BA. Even with significant reduced catalyst to initiator concentration ratios, polymerization of MA with Me$_6$TREN proceeded much faster than with PMDETA and dNbpy with controlled polymerization with PDI ~1.1.

(v) Solvents

ATRP is very often performed in solution. This has the advantage that heat transfer is rather easy to control and that viscosity can be kept low, in comparison to bulk polymerization. Dilution has a significant effect on the reaction rate because $\ln[M]_0/[M]$ vs time is dependent on both $\{R\text{-}X\}_0$ and M^t_n. A lower viscosity can only be obtained at the expense of a lowered reaction rate, and a balance between reaction rate and viscosity has to be found. Most ATRP reactions are carried out in non-polar solvent, such as xylene[85] and diphenyl ether,[36] although more polar solvent have been applied as well.[36] A pre-requisite of the solvent is that it must not have any interaction with the catalyst. It has been reported that ATRP reactions in dimethyl formamide were less successful yielding polymers with relatively high polydispersities[85]. Similarly, the addition of 5% pyridine to the reaction mixture [36]caused the reaction rate to drop dramatically.

Another important aspect of the solvent is their ability to participate in side reaction. For instance, when polymerizing styrene in polar solvent at higher temperatures, an elimination reaction occurs.[86] This leads to a loss of functionality during the polymerization and should therefore be avoided in ATRP. Likewise, solvents that participate in radical transfer processes should not be used when the production of high-molecular- weight material is aimed. Due to the longer reaction time needed to produce high –molecular-weight material, the amount of dead polymeric chains as a result of chain –transfer processes is more significant.

(vi) Additives

Metal-catalyzed living or controlled radical polymerizations are slow in most cases due to low concentration of the radical species. Sometimes additives are needed for faster or better controlled polymerization. Metals alkoxides such as Al (O-i-Pr)$_3$ have been used to increase the rate of polymerization. The latter is needed in the $RuCl_2(PPh_3)_3$ polymerization of MMA to obtain good rates of polymerization and narrow polydispersities.[32] The additive most probably interacts with the metal catalyst in its higher oxidation state and affects the redox reaction leading to faster and controlled polymerization. Zero valent metals such Cu[0] was used to increase the rate of polymerization of methyl acrylate (MA).[87] The metal Cu[0] effectively reduces $CuBr_2$ into active CuBr formed during the initial period of the reaction via disproportionation. The addition of Cu(II) salts on the other hand has been used to control polymerization that proceed too quickly[88, 89]. The concentration of radicals is reduced and this result in less termination reactions. Better control of molecular weight can be obtained and the Cu(II) deactivator also gives better polydispersities. Phenols have also been found to increase the rate of polymerization of MMA whilst retaining good control. This observation was explained by the increased catalyst activity of the copper complex formed due to the coordination of phenol to the metal center.

Benzoic acids also increase the polymerization rate via displacement of the nitrogen ligand and creation of a coordination site on the metal[97]. A beneficial effect of added soluble alkali halide salt viz. LiX (X=Cl, Br) was observed in the ATRP of acrylamide in aqueous-glycerol medium (1:1 v/v)[90, 91]. The added LiX enhances the rate of deactivation (halide transfer reaction from Cu(II) to polyacrylamide radical) by lowering the aquation of deactivator Cu(II)/L (where L= bpy or PMDETA) and provide better control. The same effect was observed almost simultaneously and independently by Tsarevsky et al[92]. who conducted ATRP of two water soluble monomers like 2-hydroxy ethyl methacrylate (HEMA) and 2-(dimethylamino) ethyl methacrlate (DMAEMA) in methanol or in methanol-water medium at 25˚C or 35˚C using CuCl/byp as the catalyst and 2-bromo isobutyrate ester of poly(ethylene oxide) mono-methyl ether [MePEG(OH)] as the initiator. To suppress hydrolysis of the catalyst, tetra butyl ammonium chloride (TBAC) salts were initially dissolved in the mixture of monomer and solvent. When no $CuCl_2$ was added in the polymerization of HEMA the PDI was 2.82 at 92% conversion. After addition of 80% $CuCl_2$ the PDI decreases to 1.40. When 100 equivalent of TBAC with respect to $CuCl_2$, was also added into the mixture the PDI decreases to 1.17. A similar situation arises in the polymerization of DMAEMA. As the literature survey indicates, role of nano additives was not attempted ever in ATRP.

(vii) Effect of the Temperature on ATRP

ATRP is affected also by temperature in general, the rate of polymerization increases with temperature because both the propagation rate constant and the atom transfer equilibrium constant between dormant and active species both increased. The latter is expected from the fact that the activation energy for activation is greater than that of deactivation. Thus there will be increased concentration of active polymer radical with increase in temperature. However some catalyst may also decompose with temperature and this can cause a substantial change in k_d as well as on the control of polymerization. These are the direct influences of temperature on ATRP rate constants (k_a, k_d, and k_p)[93]. Indirectly, temperature influences the solubility of the complex catalyst which alters the reaction rate. The optimization of temperature often depends on the monomer structure and choice of the catalyst system. For example, ATRP of MMA using the CuBr/PMDETA catalyst in anisol is better controlled at ambient temperature than at higher temperature (90˚C)[44, 94]. On the other hand, with CuX(X=Cl, Br)/dNbpy catalyst, facile ATRP takes place at 90˚C[95].

1.7 Kinetics of ATRP

In as much as ATRP or for that matter other CRPs, work on the basis of the persistent radical effect, there can never be a constant concentration of the polymer radicals in the system. The radical population will increase in the beginning and then as the termination increases with the radical population, the latter beings to decrease while the deactivator concentration grows. Eventually an equilibrium is set up between the dormant chains on one hand and the polymer radicals and the deactivator on the other. The equilibrium condition for a first order dissociation of the dormant chains such as that occurs in NMP or SFRP is $k_a/k_d=K<[I]_0k_d/4k_t$. In the equilibrium regime the polymer radical concentration is so reduced that the termination becomes negligible compared to the deactivation. In a typical ATRP system, ~5% of chains are formed dead through the termination reaction; the other 95% are dormant.

The kinetic equation for the polymer radical concentration,$[P^{\bullet}]$ and the monomer disappearance for such systems were deduced by Fischer as well as by Ohno et al. which are given here as equation 1.2 and 1.3 respectively.[96, 97]

$$[P^{\bullet}] = ([R\text{-}X]_0[M_n^t]_0)^{1/3}\{ka/3kd2kt\}^{1/3}t^{-1/3} \qquad \text{(Eq.1.2)}$$

$$\ln[M]_0/[M] = 3/2\ k_p([R\text{-}X]_0)[M_n^t]_0)\{ka/3kd2kt\}^{1/3}\ t^{2/3} \qquad \text{(Eq 1.3)}$$

Where R-X and M_n^t are the initiator and the transition metal catalyst respectively. K_a, k_d, k_p and k_t are the rate constants for activation, deactivation, propagation and termination respectively.
The equations 1.2 predict that the polymer radical concentration should decay as inverse 1/3 power of time while the log [M] will decreases as 2/3 power of time. Thus the first order plot of monomer disappearance i.e. $\ln[M]_0/[M]$ vs. t plot should be linear. This follows from the following consideration.

$$-d[M]/M = kp[P]dt \qquad \text{(Eq 1.4)}$$

For a system, devoid of termination, polymer radical concentration, $[P^{\bullet}]$ is constant.
Integrating between limit t=0 and t,

$$\ln\{[M]_0/[M]\} = k_p\ [P^{\bullet}]t \qquad \text{(Eq 1.5)}$$

Equation 1.5 may be contrasted with Eq. 1.3 deduced for a persistent radical control CRP system which shows that $[M^{\bullet}]$ decays as $t^{-1/3}$ (Eq 1.3) and thus for such systems plots of $\ln[M]_0./[M]$vs $t^{2/3}$ (instead of t) should be linear.
However, in a great majority of the ATRP systems the first order plot of $\ln[M]_0/[M]$ vs. t become linear. Matyjaszewski et al. attributed this result to the decrease of kt with increase in the degree of polymerization (DP). Fukuda et al.[97], however, holds the view that the linear ATRP kinetic plot arise because of the inevitable presence of deactivator (due to the oxidation of the metal catalyst during manipulations) in the system from the very beginning.
For steady-state conditions, there are first-order dependencies on initiator and activator and inverse first-order dependence on deactivator and the time dependence are linear. It is to be noted that Eq 1.3 describes the non-steady-state polymerization rate in terms of initial concentration of initiator and activator. Eq 1.5 describes the steady-state polymerization rate in terms of concentrations at any point in the reaction as long as only short reaction intervals are considered so that concentration changes are small. Steady- state low concentrations of radicals occur when the deactivator/ activator ratio is about equal to or greater than 0.1. Non-steady-state conditions occur when the ratio is lower than 0.1. Under steady state condition radical concentration is very low and the deactivator concentration is high.

1.8 Other Diagnostic Features of Controlled Radical Polymerization (CRP)

(1) Molecular weight is proportional to conversion and DP=Pn= $[M]_0/[I]$ x Conversion (Where M_0= monomer concentration at the start or reaction, I= initiator).
For a termination free system, the above equation is obvious. However, for CRP systems which are not free from termination the above equation has been analytically shown to be applicable with the assumption that the polymerization occurs only in the equilibrium regime and some minor approximation are also required to be made[97].
(2) The polydipersity index (PDI) should be low
The PDI value as low as 1.05 has been achieved for ATRP of styrene using the soluble CuBr/4, 4'-dinonyl 2, 2'-bipyridine (dNbpy) catalyst.[36] However, for the some living systems e.g. in the ATRP of N-N-dimethyl acrylamide using Ru(II) based catalyst a value of 1.6 for PDI was reported.[62] A value of PDI ≤ 1.3 is most commonly reported in ATRP.
A low PDI requires that the initiation, activation as well as deactivation should be much faster than propagation so that all chains starts essentially at the same time and have equal opportunity to grow. The rate constant for activation should, however, be lower than that for the deactivation. This ensures that the equilibrium concentration of the polymer radicals remains low so that the termination becomes negligibly small. The following equation relating with k_d (the deactivation rate constant) and conversion has been theoretically derived. [80, 98]

$$PDI = 1 + \{[R\text{-}X]_0k_p/k_d[D]\}\ \{2/x\text{-}1\} \qquad \text{(Eq 1.6)}$$

Where [R-X] and [D] are the initiator and deactivator concentration and X is the fractional conversion of monomer to polymer. This equation predicts that the molecular weight distributions are narrower with lower initiator concentrations, higher conversions, rapid deactivation (higher values of k_d and [D]), and lower k_p value.
(3) Block copolymer synthesis
The livingness polymerization would be the test of the ability of the polymers to initiate CRP i.e. they should be able to act as macroinitiator. This can be proved by successful block copolymer synthesis and /or chain extension experiments.

1.9 Advantage of ATRP:

(i) Synthesis of block Copolymers by ATRP

ATRP can be used to prepare block copolymer with block lengths of predetermined molecular weight with narrow PDI's and polymers with varying architecture. The living nature of polymers prepared by ATRP has been exploited to make block copolymers by two general methods. Homo-polymerization of the first monomer and subsequent isolation of the resultant polymers will yield a macro-initiator with a halogen ω end-group for polymerization of the second monomer (the so called two pot method). Alternatively, the second monomer can be added directly to the reaction pot as the first polymerization nears high monomer conversion (one pot method), a method, which although more simple inevitably leads to some statistical co-polymerization of the two monomers between the blocks[42, 99]. For the preparation of the tri-block copolymer difunctional ATRP initiator example 1,2-bis(bromoisobutyryloxy) ethane are frequently used to prepare the macroinitiator which eventually forms the centre block of tri-block copolymer. Synthesis of graft copolymer is less trivial as it requires preparation of a polymer or copolymer by a separate polymerization technique with pendant groups that are initiator sites for ATRP. There are large numbers of papers on block copolymer synthesis. Only some salient features and few representative examples are given in further text.

In the block copolymer synthesis, the principal problem is the initiaton of polymerization of the second monomer by the macroinitiator. Often a combination of monomers in the block copolymer becomes such that the first monomer give a secondary radical while the second monomer a tertiary radical. Since the secondary radical is less stable, the radical generation rate from the macroinitiator would be slower so that the initiaton could be slower than propagation. In such cases the block copolymerization will lead to incomplete initiaton and bimodal MWD. An example is the initiation of MMA polymerization by poly(butyl acrylate) macroinitiator. Matyjaszewski et al[100]. solved the, problem by incrasing the initiation rate using the so called halide exchange approach. In this method the macroinitiator prepared had Br at the end of polymer chain and the catalyst used for the second stage polymerization was CuCl. Because the C-Cl bond is much stronger than C-Br, the initiation rate is vastly increased leading to efficient initiation which becomes faster than propagation. Block copolymerization becomes successful following this approach.

Moineau et al[101] carried out ATRP of MMA initiated by α,ω–dibromo poly(n-butyl acrylate)(PMA) in the presence of $NiBr_2(PPh_3)_2$ leading to poly(MMA)-b-poly(nBuA)-b-poly(MMA) triblock copolymers(M-nB-M). The initiation of MMA polymerization was slow compared to the chain propagation, which results in PMMA blocks of broad molecular weight distribution (MWD). In order to improve upon this situation several experimental parameters were varied. On replacing CuBr/dNbpy by $NiBr_2(PPh_3)_2$, the control was very poor. Then, the halide exchange was considered by substituting CuCl for CuBr. The CuCl/dNbpy catalyst proved superior to the originally used $NiBr_2(PPh_3)_2$ system. Finally, the addition of an excess of $CuCl_2$ (deactivator) to the CuCl/dNbpy catalyst was very beneficial in deceasing the MWD of PMMA blocks. Indeed, the gel permeation chromatograms were monomodal and narrow from the very beginning of the polymerization. The rheological analysis of the PMMA-b-PBA-b-PMMA triblock copolymer synthesized in the presence of each of the above mentioned catalytic systems confirmed differences in the molecular control of the copolymerization reaction.

Lee et al[102]. synthesized amphiphilic random, gradient and block copolymers of 2-(dimethylamino)ethyl methacrylate (DMAEMA) and n-butyl methacrylate by ATRP in water/2-propanol medium (10 vol% water) using a methoxy-poly(ethylene glycol) (MPEG)(Mn = 2000) macroinitiator. Kinetic studies indicated that the copolymerization was well controlled with molecular weights increasing linearly with conversion. Copolymers with molecular weights up to Mn = 43,000 and low polydispersities (PDI= 1.11-1.47) were prepared. The thermosensitivity and aggregation properties of the random, gradient and block copolymers significantly depend on the architecture of copolymers.

Percec et al[103.] synthesized α,ω-di(iodo)poly(vinyl chloride)s with number-average molecular weights (Mn) of 2100-29800 and PDI of 1.66-2.16 by the single-electron transfer/degenerative-chain-transfer mediated living radical polymerization of vinyl chloride initiated with CHI_3 and catalyzed by $Na_2S_2O_4$. These α,ω-di(iodo)poly(vinyl chloride)s were used as initiator for the metal-catalyzed living radical block copolymerization of methyl methacrylate mediated by CuCl/2,2'-bipyridine. Poly(methyl methacrylate)-b-poly(vinyl chloride)-b-poly(methyl methacrylate) block copolymers with Mn values of 36500-95700 and PDI lower than 1.20 were synthesized by this novel and general synthetic method.

They also reported the effects of various ligands on the rate of block copolymerization mediated by Cu(0)in DMSO. The block copolymerization catalyzed by Cu(0)/tris(2-dimethylaminoethyl)amine in DMSO at 90˚C yielded block copolymers in less than 15min, whereas at 25˚C, the reaction times ranged from 60 to 100 min. Therefore, this ultrafast synthetic method provided access to PMMA-b-PVC-b-PMMA, regardless of the reaction temperature, in the same range of reaction times as the induction period of the same reactions carried out at 90C in diphenyl ether and catalyzed by CuCl/2, 2'-bipyridine[104].

(ii) Synthesis of Star polymers by ATRP

Star polymers are branched polymers with several chains linked together at a single junction point. Well-defined star polymers with defined number of chains (arms), chain length, molecular weight and composition are very important to understand in general the effect of branching on the polymer structure. Different types of star polymers like homopolymers, heteroarm star polymers, star block copolymers etc are known. There are two broad approaches used for making star polymers e.g. “arm- first” and “core-first” approach. In the “arm-first” approach mono-functional, living linear macromolecules are initially synthesized then star formation occurs either of the two ways: a di-functional co-monomer is used to provide cross-linking through propagation or a multifunctional terminating agent is added connecting a precise number of arms to a central core molecule[105]. The former, micro gel, technique produces macromolecule with a large often heterogeneous number of arms while in the latter case separation technique is used to isolate star from uncoupled linear polymers. In the “core- first” method, multifunctional initiators are used to grow chains from a central core resulting in macromolecules with well-defined structure in both arm number and length. Advantage of this method is that the reaction consists solely of stars in the absence of linear polymers[106-109]. To synthesize well- defined stars, the use of initiator with precise functionality is essential. Furthermore, regular star shaped polymers can not be successfully synthesized by means of conventional free-radical polymerization, as it would inevitably result in cross-linked materials owing to uncontrolled termination reactions. Among the variety of methods reported, living polymerization seems to be the most suitable for the synthesis of branched polymers with controlled structure. Living ionic[110, 111], metathesis[112] and group transfer polymerization[113, 114] were adequate for the application, but all required strenuous methods of reagent purification. However controlled /living free radical polymerization was found to be good technique for the synthesis of polymer with controlled architequete. Specifically atom transfer radical polymerization (ATRP) provides control over chain length and functionality by equilibrium between a dormant alkyl halide and a free radical mediated by an interchange between copper (I) /copper (II) salts and the organic polymeric chain ends[115, 116-118].

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