ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

INTRAMOLECULAR CROSS-LINKING OF POLYMERS BY USING DIFUNCTIONAL ACETYLENES VIA CLICK CHEMISTRY

M.Sc. THESIS

Halime CENGİZ

Department of Chemistry

Chemistry Programme

JUNE 2012

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

INTRAMOLECULAR CROSS-LINKING OF POLYMERS BY USING DIFUNCTIONAL ACETYLENES VIA CLICK CHEMISTRY

M.Sc. THESIS

Halime CENGİZ
(509081246)

Department of Chemistry

Chemistry Programme

Thesis Advisor: Prof. Dr. Yusuf YAĞCI

JUNE 2012

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

BİFONKSİYONEL ASETİLEN GRUBU İÇEREN POLİMERLERİN KLİK KİMYASI YOLUYLA MOLEKÜL İÇİ BAĞLANMASI

YÜKSEK LİSANS TEZİ

Halime CENGİZ
(509081246)

Kimya Anabilim Dalı

Kimyagerlik Programı

Tez Danışmanı: Prof. Dr. Yusuf YAĞCI

HAZİRAN 2012

Halime Cengiz, a **M.Sc.** student of ITU **Graduate School of Science Engineering and Technology** student ID **509081246**, successfully defended the **thesis** entitled "**INTRAMOLECULAR CROSS-LINKING OF POLYMERS BY USING DIFUNCTIONAL ACETYLENES VIA CLICK CHEMISTRY"**, which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Prof. Dr. Yusuf YAĞCI** ....
İstanbul Technical University

Jury Members : **Prof. Dr. A. Tuncer ERCİYES** ....
İstanbul Technical University

Prof. Dr. Turan ÖZTÜRK ....
İstanbul Technical University

Date of Submission : 04 May 2012
Date of Defense : 04 June 2012

To my father,

ACKNOWLEDGMENTS

It is a great pleasure to thank my supervisor Prof. Dr. Yusuf Yağcı for his invaluable gudience, support, suggestions and stimulating advice for the completion of my thesis.

I also would like to thank Prof. Dr. Levent Toppare for his valuable helps, advices and supports during my studies at METU.

I owe great thanks to Dr. Binnur Aydoğan, technical support and answering my questions any time in the laboratory, becides her kind friendship.

I wish to deeply thank to all the members of Yagci Lab for all their help, support and friendship.

Words fail to express my eternal gratitude my parents Zehra and Muhsin Cengiz, sister Zeynep Cengiz İbili and her husband Fatih İbili, my brother Veysel Cengiz and his wife Ayşe Cengiz and little ladies of our familiy Cansu Cengiz and Duygu Cengiz, for giving me the intellectualand emotional guidance that made me who I am, and for their never anding suppport, encouragement along with understanding for my frequent absences.

Finally, I would like to thank my friend Ersin Yıldız for his help and encouragement.

June 2012 Halime CENGİZ
Chemist

TABLE OF CONTENTS

Page

ABBREVIATIONS

^{1}H-NMR : Nuclear Magnetic Resonance Spectroscopy
GPC : Gel Permeation Chromatography
FT-IR : Fourier Transform Infrared Spectroscopy
DPD : 1,10-Dipropargyloxy Decane
P(S-co-CMS) : Poly(styrene-co-chloromethylstyrene)
PS-N_3 : Polystyrene-azide
$CDCl_3$: Deuterochloroform
DSC : Differential Scanning Calorimetry
PNP : Polymeric Nanoparticles
DEB : 1,4-diethynylbenzene
CuAAC : Copper(I)-catalyzed Azide-alkyne
DA : Diels-Alder
CMS : Chloromethyl Styrene
AIBN : 2,2-azobisisobutyronitrile
THF : Tetrahydrofuran
DMF : Dimethylformamide

LIST OF TABLES

Page

LIST OF FIGURES

LIST OF SCHEMES

Page

INTRAMOLECULAR CROSS-LINKING OF POLYMERS BY USING DIFUNCTIONAL ACETYLENES VIA CLICK CHEMSTRY

SUMMARY

Polymeric nanoparticles (PNP) are fastly sprawling and have crucial role in areas of life during last decades. Their incomparable properties increase this trend and give a lot of application areas at marked needs such as, medicine to biotechnology, conducting materials to sensors and electronics to photonics. Advances in polymerization chemistries and the application of reactive, efficient and orthogonal chemical modification reactions have enabled the engineering of multifunctional polymeric nanoparticles with precise control over the architectures of the individual polymer components, to direct their assembly and subsequent transformations into nanoparticles of selective overall shapes, sizes, internal morphologies, external surface charges and functionalizations.

Different synthesis methods are described in literature to get polymeric nanoparticles. Over the last decade, growing interest has been devoted to the use of rapid reactions that meet the three criteria of an ideal synthesis: efficiency, versatility and selectivity. The most popular reactions that have been adapted to fulfill these criteria are known as “click” reactions. Controlled size and prespecified adjustment of functional group polymers give rise to a path of obtainig nanoparticles. With the help of functional groups, polymer can cross-link intramolecularly at ultra dilute conditions which is one of the most popular synthesis methods of polymeric nanoparticles.

In this study, an efficient approach was described for the intramolecular crosslinking of azide functionalized poly(styrene-*co*-chloromethyl styrene) copolymers (PS-N_3) with appropriate diacetylene functional compounds in ultra-dilute conditions via click chemistry at room temperature. Reaction of azide functionalized poly(styrene-*co*-chloromethyl styrene) copolymers (PS-N_3) with the appropriate diacetylene functional compounds such as 1,4-diethynylbenzene (DEB) and 1,10-dipropargyloxy decane (DPD) in ultra-dilute solutions led to unimolecular particle-like structures. The resulting molecules are also soluble in common organic solvents. The resulting cyclic polymers were characterized in detail by using ^{1}H-nuclear magnetic resonance spectrometry (NMR), fourier transform infrared spectrometry (FTIR), gel permeation chromatography (GPC) and differential scanning calorimetry (DSC) measurements. In addition to these analyses, shear rate dependence with viscosity measurements of the obtained polymers were investigated.

In conclusion, the use of click reaction as a versatile synthetic route to prepare cyclic polymers was demostrated. Azide functionalized copolymers were intramolecularly cross-linked with appropriate diacetylene functional compounds in ultra-dilute conditions via click chemistry approach. The structures of obtained particle-like structures have been fully characterized.

BİFONKSİYONEL ASETİLEN GRUBU İÇEREN POLİMERLERİN KLİK KİMYASI YOLUYLA MOLEKÜL İÇİ BAĞLANMASI

ÖZET

Günlük yaşamın çeşitli bölümlerinde önemli bir yer alan polimerik nanopartiküller (PNP) hızla gelişmektedir. Benzersiz özelliklere sahip olmaları, kendilerine olan ilgiyi ve kullanım alanlarını arttırmaktadır. Biyoteknoloji, ilaç, iletken polimerler, sensörler, elektronikler kullanım alanlarından yalnızca birkaçıdır.

Polimerizasyon kimyasındaki gelişmeler ve etkili kimyasal modifikasyon reaksiyonları çok fonksiyonlu polimerik nanopartiküllerin üretilmesini sağlamakla beraber, polimer bileşkilerin istenilen düzeyde kontrol edilmesini, istenilen şekil ve boyutlarda sentezlenmesine imkan vermektedir. Buna ek olarak polimerik nanopartiküller fonksiyonellik bakımından uygulanacağı alanlarda iç ve dış yüzey morfolojilerinde istenilen düzeyde değişiklik yapılmasını sağlamaktadır.

Polimerik nanopartiküller elde etmek için literatürde çeşitli yöntemler bulunmaktadır. Geçtiğimiz son on yılda, ideal sentezin üç kriteri olan etkinlik, çeşitlilik ve seçicilik özellklerini karşılayan hızlı reaksiyon sistemlerine olan ilgi hızla artmıştır. Bu kiriterleri yerine getiren en popüler reaksiyonlar “klik” reaksiyonları olarak bilinmektedir. Kontrollu boyutta ve belirlenmiş fonksiyonel grupları olan polimerler nanopartikül oluşturmak için bir yöntem sağlamaktadır. Bu fonksiyonel gruplar sayesinde, aşırı seyreltik koşullarda polimerlerin molekül içi bağ yapmaları sağlanabilmekte ve nanopartikül boyuta ulaşılabilmektedir. Fonksiyonel grupları olan polimerler ile nanopartikül boyutta ürün eldesi dikkat çekici ve popüler bir yöntemdir.

Bu çalışmada, etkili bir yöntem olan azit fonksiyonlu poli(stiren-co-klorometil stiren) kopolimerinin (PS-N_3) ultra saf koşullarda ve oda sıcaklığında klik kimyası yardımı ile molekül içi bağlanması tanımlanmıştır. Stiren ve klorometil stiren’nin öncül kopolimerleri 2,2-azobisisobutyronitril (AIBN) ile başlayan serbest köksel atom polimerizasyonu yoluyla sentezlenmiştir. Üretilen kopolimerlerin kompozisyonları ^{1}H-nükleer manyetik rezonans spektrometrisi (NMR) ile belirlenmiştir. Stiren ve klorometil stiren’nin mol fraksiyonları klorometil stiren (CMS)’de klorin atomuna bağlı metilen protonlarının 4,5 ppm civarındaki sinyal alanlarının 6,6 ppm ile 7,4 ppm arasındaki, bu alan toplam aromatik protonlarını temsil eder, toplam sinyal alanına oranı ile hesaplanmıştır.

Üretilen poli(stiren-co-klorometil stiren) kopolimerlerinin (P(S-co-CMS)) molar kompozisyonları ve ortalama moleküler ağırlıkları jel geçirgenlik kromatografisi (GPC) ile belirlenmiştir. Daha sonra azid yan grubu içeren kopolimerleri elde etmek amacıyla sodyum azid (NaN_3) kullanılarak azidasyon prosedürü gerçekleştirilmiştir. Poli(stiren-co-klorometil stiren) kopolimerinin (PS-N3) ^{1}H- nükleer manyetik rezonans spekturumunda, 4,2 ppm de ortaya çıkan yeni sinyal azid grubuna bağlı metilen protonuna ait olup, 4,5 ppm‘deki sinyal tamamiyle kaybolmuştur. Klik reaksiyonlarında kullanılan diğer komponentler alkin içeren diasetilen fonksiyonel bileşikleri olan 1,4-diethynylbenzen (DEB) ve 1,10-dipropargloksi dekan (DPD) olarak seçilmiştir. DPD ticari olarak bulunmakla beraber propargil bromid kullanılarak basit esterifikasyon reaksiyonuyla sentezlenmiştir.

Son adımda, oda sıcaklığında Cu(I) katalizi ile birlikte molekül içi bağlanma klik reaksyonu gerçekleştirilmiştir. Bu reaksiyonda azid fonksiyonlu poli(stiren-co-klorometil stiren) kopolimer (PS-N3) solüsyonu diasetilen içeren solüsyona damla damla eklenmiştir. Bu ekleme sonucu poli(stiren-co-klorometil stiren) (PS-N3)'in azidleri ile 1,4-diethynylbenzen (DEB) ve 1,10-dipropargloksi dekan (DPD)'in diasetilen fonksiyonları arasında CuBr/bpy ile katalize edilmiş triazol oluşumu gerçekleştirlmiştir. Elde edilen polimerler metanol içinde çöktürülerek nicel olarak saflaştırılmıştır. Daha sonra polimerler jel geçirgenlik kramotografisi (GPC), Fourier transform kızıl ötesi spektrometrisi (FTIR) ve ^{1}H-nükller manyetik rezonans (NMR) spektrometri yöntemleri ile karakterize edilmişlerdir.

Azid fonksiyonlu polimerlerin moleküler ağırlıkları klik reaksiyonları sonucunda molekül için bağlanmadan dolayı büyük miktarda azalmıştır. Molekül içi halka bağlanmaları molekül içi düz zincirlerin daralmalarına sebep olur. Bu yolla üretilen halka polimerlerde polidispersite ve hidrodinamik hacim değişmeden moleküler ağırlıklarında büyük miktarda azalmalar meydana gelir. Polimerlerin hidrodinamik hacimlerindeki yapısal etkiyi incelemek amacıyla farklı zincir yapılarına sahip olan 1,4-diethynylbenzen (DEB) ve 1,10-dipropargloksi dekan (DPD) ile ikinci bir set polimerler üretilmiştir.

Sonuçlar 1,10-dipropargloksi dekan (DPD) ile kliklenen polimerin hidrodinamik hacminin % 50 oranında azaldığını ancak 1,4-diethynylbenzen (DEB) ile kliklenen polimerin hidrodinamik hacminin sadece % 30 oranında azaldığını göstermiştir. 1,4-diethynylbenzen (DEB) ile kliklenme gerçekleştiğinde meydana gelen düşük orandaki, azalma 1,4-diethynylbenzen (DEB)'in merkez aromatik halkasından dolayı sahip olduğu rijit yapısından kaynaklanmaktadır. Ayrıca 1,4-diethynylbenzen (DEB) ile elde edilen halka polimerler tetrahydrofuran (THF) ve dimetilformamid (DMF) gibi solventlerde düşük miktarda çözünme göstermiştir.

Molekül içi bağlanmayı doğrulamak amacıyla halka polimerlerden bir tanesi seçilerek spektroskopik olarak incelenmiştir. Klik reaksiyonundan önce ve sonra çekilen nükller manyetik rezonans spektrometrilerinde 4,2 ppm'de görülen azid grubuna bağlı metilen protonlarının tamamiyle yok olarak yerine 5,3 ppm'de triazol halkasına bağlı metilen protonlarının sinyalinin ortaya çıktığı gözlemlenmiştir. Fourier transform kızıl ötesi spektrometrisi de başarılı bir klik reaksiyonunu doğrulamaktadır. Klik reaksiyonundan sonra 2095 cm^{-1} de görülen $-N_3$ bandı tamamiyle yok olmuştur.

Jel geçirgenlik kromatografisi (GPC) sonuçları da halka polimerin moleküler ağırlığının azid fonksiyonlu başlangıç polimerinin moleküler ağırlığından daha düşük olduğunu göstermiştir. Poli(stiren-co-klorometil stiren) kopolimerin (PS-N_3) ve halka polimerin camsı geçirgenlik sıcaklıkları diferansiyel tarama kalorimetrisi (DSC) ile ölçülmüştür. Poli(stiren-co-klorometil stiren) kopolimerinin (PS-N_3) camsı geçirgenlik sıcaklığı zincir mobilitesi düştüğünden dolayı 95°C'den 132°C'ye kaymıştır.

Poli(stiren-co-klorometil stiren) (P(S-co-CMS))'in, poli(stiren-co-klorometil stiren) kopolimerinin (PS-N3) ve halka polimerlerin viskozitelerine bağlı kayma oranları da ayrıca incelenmiştir. Aynı konsantrasyonlar ile incelenen örnekler ile elde edilen data viskozitelerde açık bir değişimi göstermektedir. Halka polimerin oluşumundan sonra viskozitede meydana gelen azalma polimerin düz bir molekül davranışı yerine partikül benzeri davranış göstermesinden kaynaklanmaktadır.

Sonuç olarak, halka polimerlerin sentezinde uygulanabilen klik reaksiyon profili gösterilmiştir. Azid fonksiyonlu kopolimerler uygun diasetilen fonksiyonlu bileşikler ile ultra saf koşullarda klik kimyası yoluyla molekül içi bağlanmıştır.

Son zamanlarda benzersiz özelliklere sahip olmaları, biyoteknoloji, ilaç, iletken polimerler, sensörler, elektronikler gibi kullanım alanlarına sahip olan bu partikül benzeri yapılar nükleer manyetik rezonans spektrometrisi (NMR), fourier transform kızıl ötesi spektrometrisi (FTIR), diferansiyel tarama kalorimetrisi (DSC) ve jelleşme geçirgenlik kromatograifis gibi yöntemlerle karakterize edilmiştir. Elde edilen polimerlerin viskozitelerine bağlı kayma oranları da ayrıca incelenmiştir.

1. INTRODUCTION

There has been revitalized interest in the preparation of polymeric nanoparticles due to the use of these tailor-made materials in a variety of applications such as microelectronics [1, 2], drug delivery systems [3-7], polymer processing [8-10], etc. Recently, several strategies were employed for the preparation of polymeric nanoparticles including intramolecular cross-linking of single polymer chains containing cross-linkable groups at ultra-diluted reaction conditions [11-17] and single-chain collapse of macromolecules containing suitable reactive groups along the chain with bifunctional cross-linkers [18, 19].

Cu(I)-catalyzed Huisgen 1,3-dipolar cycloaddition reactions [20] between an azide and an alkyne, known as “click” reactions have attracted much attention due to their important features such as high yields, short reaction times, high tolerance of functional groups, and selectivity [21-23]. The Diels-Alder cycloaddition reaction [24-26] and thiol-ene chemistry [27, 28] have recently been introduced as alternative click routes for providing new materials. Click reactions have been widely used for the synthesis of polymers with different compositions and topologies, ranging from linear (telechelic [29], macromonomer [30, 31], macrophotoinitiator [32, 33] and block copolymer [34-36]) to nonlinear macromolecular structures (graft [37-39], star [40, 41], miktoarm star [42, 43], H-type [44], dendrimer [45-47], dendronized linear polymers [48, 49], macrocyclic polymers [50, 51], self-curable polymers [52-54], network systems [55, 56] and polymeric nanoparticles [14, 57]). The development and application of click chemistry in polymer and material science have recently been extensively reviewed [58-63].

2. THEORETICAL PART

2.1 Polymerzation Processes

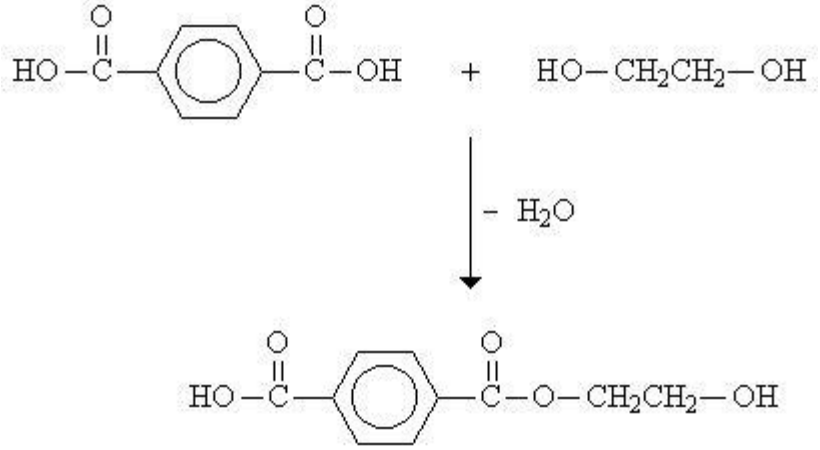
Basically, a polymerization process is based on a repetetive reaction in which a monomer converted into a polymer segment. The word *polymer* is derived from a classical Greek ***poly*** meaning “many” and ***meres*** meaning “parts”. Thus a polymer is a large molecule build up by the repetition of small chemical units. There can be hundreds or more monomer units linked together in a polymer molecule.

Throughout improvement of polymer science, two types of classification have come into use. First one is based upon structure and divides polymers as *condensation* and *addition* polymers, the other one classified the polymers by their polymerization mechanizms, as the terms *addition* and *chain*. Probably the most general classification is based on polymerization mechanism involved in polymer synthesis. Under this scheme, polymerization processes are classified as step-reaction (condensation) or chain reaction (addition) polymerization [65].

Because of most condensation polymers formed by step polymerization and most of addition polymers produced by chain polymerization, the terms *condensation* and *step* are often used as synonymously as the terms *addition* and *chain* [66]. The following section will deal with, *Condensation Polymerization* and *Chain Polymerization*.

2.1.1 Condensation polymerization

Historically the oldest class of common synthetic polymers are condensation polymers, also known as step growth polymers. Condensation polymerization occurs when a polymer is formed from a reaction that leaves behind a small molecule, often water (Scheme 2.1). Condensation polymerization involves a series of reactions inwhich two species (monomers, dimers, trimers, etc.) can react at any time, leading to a larger molecule. Condensation accompanied by the elimination of small molecules such as HCl or water as a by-product. Step-growth polymerizations generally involve either one or more types of monomer. In either case, each monomer has at least two reactive groups. In cases where only one type of monomer is involved, which is known as A-B step-growth polymerization, the fuctional groups on monomer are different and capable of intramolecular reactions. An example is the polymerization reaction involving terephthalic acid and ethylene glycol, both of which are bifunctional.



Scheme 2.1 : Example of condensation polymerization

The monomers that are involved in condensation polymerization are not the same as those in addition polymerization. The monomers for condensation polymerization have two main characteristics.

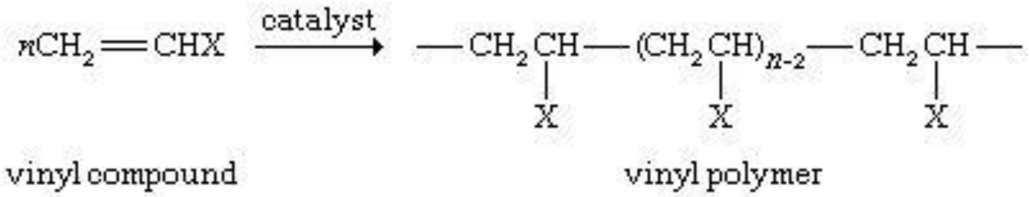
a) Instead of double bonds, these monomers have functional groups (like alcohol, amine, or carboxylic acid groups).

b) Each monomer has at least two reactive sites, which usually means two functional groups.

Some monomers have more than two reactive sites, allowing for branching between chains, as well as increasing the molecular mass of the polymer. To get the polymers, the monomers must be at least difunctional; monofunctional reactants disrupt the polymer growth. [65-66].

2.1.2 Chain-reaction polymerization

Chain-reaction polymerization, is one of the most important industrial method to get polymers, which involves the addition of unsaturated molecules to a rapidly growing chain (Scheme 2.2). Olefins are the most common unsaturated compounds that go to chain reaction polymerization.



Scheme 2.2 : Example of vinyl polymerization by chain-reaction polymerization.

The growing polymer in chain-reaction polymerization is a free radical, and polymerization proceeds via chain mechanism. Chain-reaction polymerization is indused by the addition of free radical forming reagents by ionic initiators. Like all chain reactions, it involves three fundemental steps: the reaction gets started initiation, the reaction keeps going propagation, and the reaction stops termination. The first reactant is known as a monomer, link in a polymer chain. It initially exists as simple units. Generally, the monomers have at least one carbon-carbon double bond. The other reactant is catalyst. In chain- reaction polymerization a free radical is formed which is a chemical component that contains a free electron and forms a covalent bond with an electron on another molecule so polymerization occurs.

First step **Initiation** involves the development of an active side by the monomer. This may occur spontaneously by the absorbtion of heat, light, or high energy irradiation. The double of monomer breaks apart, monomer bond to free radical and the free electron is transferred to the outside carbon atom in this reaction.

Second step **Propagation,** the initiated monomer adds to the other monomer. Addition of free radical to the double bond of monomer, with regeration of another radical.

The active center is thus continuously relocated at the end of growing polmer chain. Propagation is able to occur consistently because the energy in the chemical system is lowered as the chain grows. This step continues until the growing chain radical is deactivated by chain termination.

The last step **Termination** the growth activity of a polymer chain radical is destroyed by reaction with another free radical in the system to produce polymer molecules. Termination reactions are more important in polymer production are combination and disproportionation. In termination by combination, two growing polymer chain react with eachother and destruct the growing activity. In disproportionation, unstable atom transferred from one polymer chain to the other. Coupling reactions generate a single polymer where as disproportionation generates two polymers from two reacting polymer chain radicals. The dominant termination depends on nature of the reactant monomer. Disproportionation needs energy to break the chemical bonds and take place at high reaction temperatures. Combination of growing polymer radicals predominates at low temperatures. [65-66].

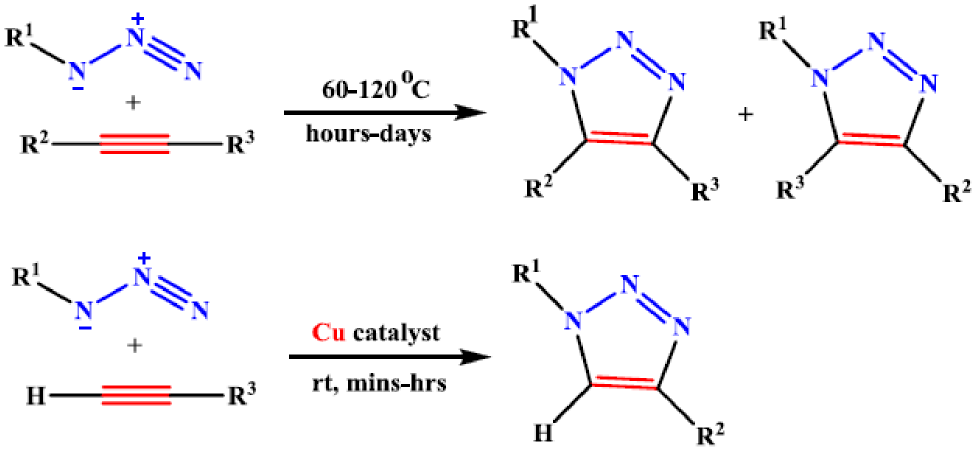
2.2 Click Chemistry

Sharpless introduced the click chemistry at 2001 and to form the substances quickly and confidently by joinig small parts together. [67] Sharpless also introduced lots of advantages of click reactions which are, high yielding, create only innocuous by-products, are stereospecific, simple to perform and that need riskless or easily removed solvent. Click chemistry concept was developed with the interest in the pharmaceutical, materials, and other industries. There are several processes have been identified under this term in order to meet these criterias such as nucleophilic ring opening reactions; non-aldol carbonyl chemistry; thiol additions to carbon–carbon multiple bonds (thiol-ene and thiol-yne); and cycloaddition reactions. Copper(I)-catalyzed azide-alkyne (CuAAC) and Diels-Alder (DA) cycloaddition reactions and thiol-ene reactions are much popular among the chemists either the synthetic or the polymer chemists. The “click”reactions generally include the formation of a carbon-heteroatom bond and the following classes of chemical transformations ;

- Cycloadditions of unsaturated species generally take place with Huisgen 1,3-dipolar Cycloaddition and Diels-Alder reaction.
- Nucleophilic ring-opening reactions of strained heterocyclic electrophiles (such as epoxides, aziridines, aziridinium ions and episulfonium ions)
- Non-aldol type carbonyl chemistry (such as formation of aromatic heterocycles, oxime ethers, amides and hydrazones)
- At the oxidative cases addtion of carbon-carbon multiple bonds.

2.2.1 Copper-catalyzed azide-alkyne cycloadditions

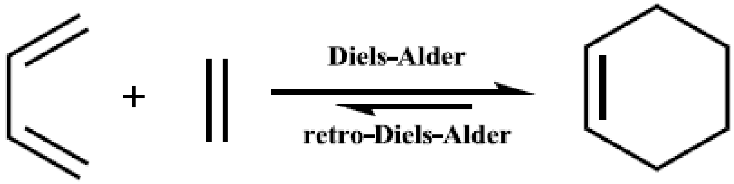
Rolf Huisgen and co-workers in the 1950s to the 1970s were subject of intensive research about 1,3-Dipolar cycloaddition reactions which called as copper(I)-catalyzed Huisgen 1,3-dipolar cycloaddition (CuAAC) reaction between azides and terminal alkynes. That is the most prominent example of “click chemistry”, discovered by the groups of Sharpless [68] and Meldal [69] (Scheme 2.3). The **Cu**-catalyzed **a**zide–**a**lkyne 1,3-dipolar **c**ycloaddition (CuAAC) dramatically accelerates the reaction of azides with terminal alkynes. It is very robust, general, insensitive, and orthogonal to most other chemistries used in synthesis of polymers [70]. Click chemistry used at a lot of fields of chemistry such as, pharmaceutical chemistry [67], supramolecular chemistry [71], and widely at organic chemistry because of its favourable advantages. Unlikely uncatalyzed cycloadditions of azides and alkynes, Cu(I) catalyzed reactions allows very fast and regioselective formation of only the 1,4-triazoles at mild reaction conditions such as low temperatures and absence of side products.



Scheme 2.3 : General represantation of thermal and cupper catalyzed cycloaddition.

2.2.2 Diels-Alder click chemistry

Professor Otto Diels and his student Kurt Alder received the Nobel Prize in 1950 for their discovery of a reaction which is called by their name “The Diels-Alder “(DA) reaction. [72]. The Diels-Alder (DA) reaction is one of the most common reactions used in organic chemistry and is a type of cycloaddition reactions. Two in a diene and one in a dienophile, totaly three p bonds, recompose to give a six-membered ring in all Diels-Alder reactions. Although Diels-Alder reaction are used in organic chemistry for many years, it gained popularity in the field of materials science with the discovery of “click chemistry”. The majority of “click” reactions generally create new carbon-heteroatom bonds, where as Diels-Alder “click” reactions create new carbon-heteroatom bonds and carbon-carbon bonds. This property increases the interest on this reaction at the chemistry world. The DA reaction, shown its general form in Scheme 2.4, involves a [4+2] cycloaddition reaction between an electron-rich diene (furan and its derivatives, 1,3 cyclopentadiene and its derivatives etc.) and an electron-poor dienophile (maleic acid and its derivatives, vinyl ketone etc.) to form a stable cyclohexene adduction [73-74].

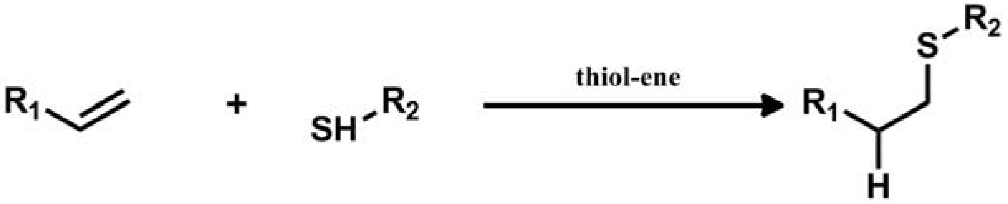


Scheme 2.4 : General mechanism of Diels-Alder/retro Diels-Alder reactions of dienophile and diene.

2.2.3 Thiol-ene click chemistry

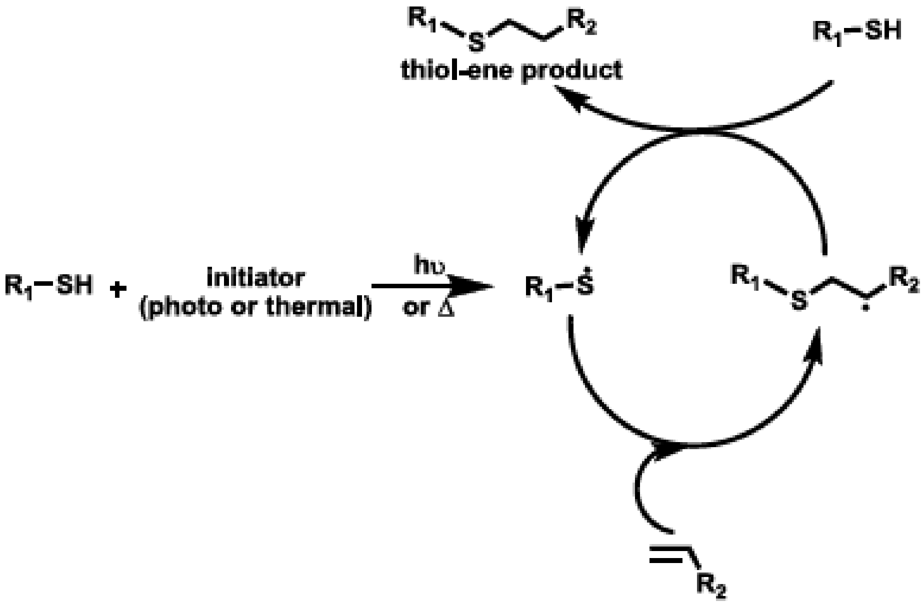
The radical addition of thiols to carbon-carbon double bonds is called as thiol-ene reaction and discovered in the early 1900s by Posner. In Thiol-ene reactions (Scheme 2.5) S-H bonds formed to a double or triple bond by either a free radical or ionic mechanism. During the proceeds a typical chain process with initiation, propagation and termination steps take place, in Scheme 2.6. At the Initiation step thiol interact with photoinitiator, on light exposure, resulting in the formation of a thiyl radical, RS˙. Propagation steps incorporate with attachment of thiyl radical to the C=C bond and hydrogen abstraction of a thiol group by a carbon-centered radical resulting the synchronous generation of a new thiyl radical, respectively and lastly Termination takes place radical–radical coupling processes.

Basically sulfur version of the hydrosilylation reaction is called Thiol-ene reactions. Thiols are also known as transfer agents and their reaction with alkenes conducted under radical conditions, photochemically and thermally [75-78] absence of side reactions.Thiol-ene reactions are considered as “click” reactions because of high yielding, efficient reactions, tolarence of solvents and functional groups [79].



Scheme 2.5 : Example of conglomeration of Thiol-ene

These reactions can be considered as friendly to the earth processes because they proceed in the absence of solvent under reversible reaction conditions out of the use of any potentially toxic metal. In order to ensure completion of reaction absence of byproduct formation, a large excess of one of the reagents should be used.



Scheme 2.6 : Schematic diagram of cross-linking.

2.3 Crosslinking Reactions of Polymers

There are a lot of techniques for polymer modifications, Cross linking is one of the prime of them. Cross linking is a multicomponent polymer system. Combining more than one functional components in a single polymer makes them attractive in the industrial field.

Crosslinking can be accomplished chemically or by irradiation. Chemically one accomplished by a heat induced reaction between the polymers and a crosslinking agent. Crosslinked by irradiation means, high energy electrons bombard the insulation system.

Crosslinking is a multidirectional chain extension of polymers by which network structures are formed. Cross linking can take place either polymerization of monomers with functionality greater than 2 or by covalent bonding between preformed polymer molecules. With the help of cross linking polymers get more resistance to heat, light, and other physical agencies, giving it a high degree of dimensional stability, mechanical strength and chemical and solvent resistance. Although some loss of strength still can take place at high temperatures, crosslinked molecular chains are much more resistant to flow when stress is applied. Degree of cross linking have an important impact on regularity of the network formed, and presence and absence of crystallinity in the polymer. If the degree of crosslinking is low, the polymer is more elastic, have lower melting point, and become softener. Decrease in free volume by closslinking, raises the glass transition temperature of the material. Because of these effcets of cross linking on polymers, it can not be avoided at the poymer chemistry.

All materials can not be crosslinked. The polymers should have some properties to crosslink, some of these are: Higher tensile strength, Improved fluid resistance, Improved abrasion/cut through, Slightly better flame resistance, Better crush resistance, No change of electricals, Solder iron resistance, Negligible change in thermal stability, Decrease in flexibility, Better over load characteristics, Resistance to stress cracking, Improved high temperature mechanicals [80].

Cross-linked reactions can take place as intra-molecularly or inter-molecularly (Figure 2.1). Intra-molecular cross-linked reaction form within a polymer molecule, and inter-molecular cross-linked reaction that takes place among different polymer molecules [81].

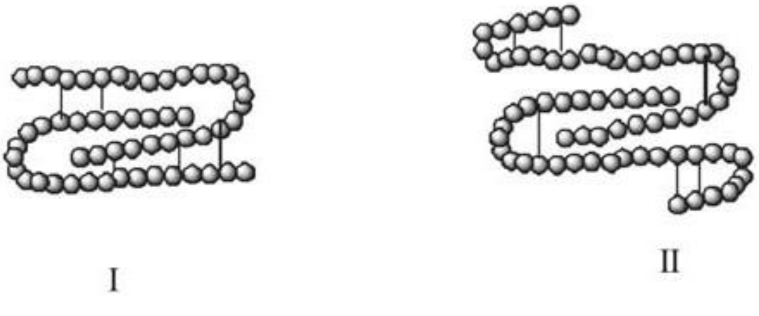


Figure 2.1 : Schematic diagram of (I) intermolecular crosslinking and (II) intramolecular crosslinking.

2.4 Polymeric Nanoparticles

Particles that have 100 nanometers or less in size called as nanoparticles. The properties of many conventional materials change when nanoparticles formed from conventional materials their properties changes because nanoparticles have a greater surface area per weight than larger particles and become more reactive to certain other molecules. Various usage advantages as implants for tissue regeneration, such as in bone, cartilage,vascular, bladder, and neuronal regeneration icreased the interest on nanoparticles [80].

The preparation of polymeric nanoparticles with controlled size and fuctional group arrangements is one of the most popular topics in recent years because of applications in the fields of microelectronics, drug delivery, polymer processing, etc. The high ratio of surface to volume of the nanophase polymer provides an important role in enhancing the physical, thermal, and mechanical properties [82]. To address the need for nanoparticles, intramolecular coupling and collapse of single copolymer chains involving reactive cross-linking groups give discrete nanoparticles which has been proposed and successfully carried out.

Shortly before, an intramolecular cross-linking reaction was achieved, where the reaction was applied under ultradilute solution. Under these conditions, the covalent links are principally formed between functional of the same polymer chain, leading to a unimolecular particle with size ranging from 3 to 15 nm [16].

3. EXPERIMENTAL WORK

3.1 Materials and Chemicals

3.1.1 Reagents

Styrene (S, 99%, Aldrich) and 4-vinylbenzyl chloride (choloromethyl styrene, CMS, 90%, Acros) were distilled under reduced pressure before use. 2,2′-azobisisobutyronitrile (AIBN, 98%, Aldrich) was recrystallized from ethanol. Tetrahydrofuran (THF, 99.8%, J.T. Baker) was dried and distilled over benzophenone-Na. 2,2′-Bipyridyl (bpy, ≥99%, Aldrich), copper(I)bromide (CuBr, ≥97.0%, Riedel-de Haën), methanol (+99%, Acros Organics), sodium hydride (NaH, 98%, Fluka), sodium azide (NaN_3, ≥99%, Merck), 1,10-decanediol (≥99%, Aldrich), propargyl bromide (80% volume in toluene, Fluka) and 1,4-diethynylbenzene (DEB, 96%, Aldrich) were used as received.

3.2 Equipments

3.2.1 ^{1}H-Nuclear magnetic resonance spectroscopy (^{1}H-NMR)

^{1}H-NMR spectra of 5–10 % (w/w) solutions in $CDCl_3$ with Si(CH3)4 as an internal standard were recorded at room temperature at 250 MHz on a Bruker DPX 250 spectrometer.

3.2.2 Gel permeation chromatography (GPC)

Gel permeation chromatography (GPC) measurements were obtained from a Viscotek GPCmax Autosampler system consisting of a pump, a Viscotek UV detector and Viscotek a differential refractive index (RI) detector. Three ViscoGEL GPC columns (G2000HHR, G3000HHR and G4000HHR), (7.8 mm internal diameter, 300 mm length) were used in series. The effective molecular weight ranges were 456–42,800, 1050–107,000, and 10,200–2,890,000, respectively. THF was used as an eluent at flow rate of 1.0 mL min^{-1} at 30°C. Both detectors were calibrated with PSt standards having narrow molecular weight distribution. Data were analyzed using ViscotekOmniSEC Omni-01 software. Molecular weights of polymers were calculated with the aid of polystyrene standards.

3.2.3 Fourier transform infrared spectroscopy (FT-IR)

FT-IR spectra were recorded on a Perkin-Elmer FT-IR Spectrum One-B spectrometer.

3.2.4 Viscosity measurements

Viscosity measurements were carried out using Brookfield Cap 2000+ viscometer (low torque, low temperature, spindle no: 1, temperature : 25°C) with the solutions prepared 2 days before measurement by dissolving the polymers in DMF followed by filtering through a 0.45 μm filter.

3.3 Preparation Methods

3.3.1 Synthesis of 1,10-dipropargyloxy decane (DPD)

1,10-Dipropargyloxy decane (DPD) was synthesized using a previously reported procedure [64]. ^{1}H-NMR (CDCl3 250 MHz): δ 4.08 (d, 4H, -OCH2CH), 3.46 (t, 4H, -CH2OCH2CH), 2.38 (t, 2H, -OCH2CH), 1.55 (m, 4H, -CH2-CH2OCH2CH), 1.25 (m, 12H, CH2). FT-IR (ATR): ν (cm^{-1}) 3305, 2923, 2850, 2112, 1455, 1355, 1264, 1091, 1018, 908, 809, 672, 635.

3.3.2 Procedure for the synthesis of poly(styrene-co-chloromethylstyrene) P(S-co-CMS)

P(S-co-CMS) was prepared by free radical polymerization (FRP) in the presence of 2, 2′-azobisisobutyronitrile (AIBN) under nitrogen atmosphere. To a flask equipped with a magnetic stirring bar, styrene (S) (4 mL, 0.035 mol), CMS (0.87 mL, 6.2 mmol), and AIBN (0.0135 g, 0.0824 mmol) were added in that order. The reaction flask was placed in a thermostated oil bath at 60 oC for 18 h. Subsequently, the polymerization mixture was diluted with THF and precipitated in excess methanol. The polymer was dried for 24 h in a vacuum oven at 25 ^{o}C. 1H NMR (CDCl3 250 MHz): δ 7.5-6.2 (m, 9H), 4.5 (s, 2H), 2.1-1.2 (m, 6H). FT-IR (ATR): ν (cm^{-1}) 3026, 2922, 1601, 1493, 1452 , 757, 695, 676.

3.3.3 Typical procedure for the synthesis of polystyrene-azide (PS-N3)

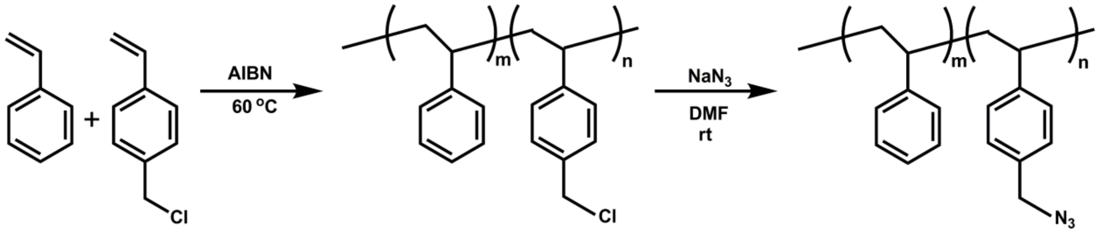
P(S-co-CMS) (1.5 g, 0.28 mmol) was dissolved in 30 mL DMF, and NaN3 (1.56 g, 24 mmol) was added. The resulting solution was allowed to stir at 25 °C overnight and precipitated in excess methanol. After filtration, the polymer was dried for 24 h in a vacuum oven at 25°C (Mn,GPC = 65800, Mw/Mn= 3.5). 1H NMR (CDCl3 250 MHz): δ 7.40–6.20 (m, 9H), 4.25 (s, 2H), 2.1-1.2 (m, 6H). FT-IR (ATR): ν (cm^{-1}) 3025, 2922, 2095, 1680, 1601, 1493, 1452, 757, 698.

3.3.4 General procedure for cyclic polymer formation via click chemistry

The azide functionalized copolymer 1 (0.1 g, 1.27 μmol and 0.19 mmol equiv of N_3) was dissolved in 30 mL of freshly distilled THF. In a round-bottom flask DPD (121 mg, 0.095 mmol), CuBr (35.43 mg, 0.247 mmol) and bpy (77 mg, 0.494 mmol) were dissolved in 30 ml of freshly distilled THF. The THF solution of copolymer 1 was added dropwise via dropping funnel to the flask over a 90 min period with vigorous stirring and the mixture was allowed to stir for 24 h. At the end of this period, polymer solution was precipitated into methanol then dissolved in THF and passed through alumina column to remove copper salt. Finally, it was dried in a vacuum oven at 25 °C. ^{1}H-NMR ($CDCl_3$ 250 MHz): δ 8.0–6.20 (m, 11H), 5.3-5.6 (s, 2H), 2.1-1.2 (m, 6H). FT-IR (ATR): ν (cm^{-1}) 3026, 2924, 1601, 1493, 1452, 1092, 1018, 798, 698.

4. RESULTS AND DISCUSSION

Precursor copolymers of styrene (S) and chloromethyl styrene (CMS) were synthesized by free radical polymerization initiated with 2, 2′-azobisisobutyronitrile (AIBN) (Scheme 4.1). The compositions of copolymers were determined using ^{1}H NMR spectroscopy. The mole fractions of S and CMS were calculated from the ratio of the peak areas around 4.5 ppm, corresponding to two methylene protons adjacent to chlorine atom of CMS, to the total area between 6.6 and 7.4 ppm, which was attributed to the total aromatic protons. The molar compositions and number-average molecular weights of the resulting poly(styrene-*co*-chloromethyl styrene) copolymers P(S-*co*-CMS) were determined by GPC (Table 4.1). Subsequently, P(S-*co*-CMS)s were modified by azidation procedure using NaN_3 as described in the Experimental Section to obtain copolymers with azide side groups. The experimental conditions and results are presented in Table 4.1. In the ^{1}H NMR spectrum of PS-N_3, a new signal appeared at 4.2 ppm was attributed to methylene protons linked to azide groups while the signal at 4.5 ppm disappeared completely. As alkyne containing compounds are the other antagonist components of the click reaction we chose two different diacetylene functional compounds namely, 1,4-diethynylbenzene (DEB) and 1,10-dipropargyloxy decane (DPD). DPD was synthesized by a simple etherification reaction using propargyl bromide while DEB was commercially available.



Scheme 4.1 : Synthesis of P(S-*co*-CMS) and PS-N_3.

Table 4.1 : Conditions[a] and results for the synthesis of poly(styrene-*co*-chloromethyl styrene) (P(S-*co*-CMS) and PS-N_3.

Code	(mol·L^{-1})	Time (h)	Conversion[b] (%)	$M_{n,GPC}$ [c] (g·mol^{-1})	M_w/M_n[c]	Copolymer composition[d] (mol %)	
						CMS	S
P(S-co-CMS)-1	8.5×10^{-3}	22.5	94	88600	2.45	22	78
P(S-co-CMS)-2	16.8×10^{-3}	18	87	58200	2.82	18	82
P(S-co-CMS)-3	28.8×10^{-3}	8	26	63400	1.83	21	79

[a] Feed ratio of CMS/S: 0.87 mL/ 4 mL (15/85 mol %), temperature: 60°C.

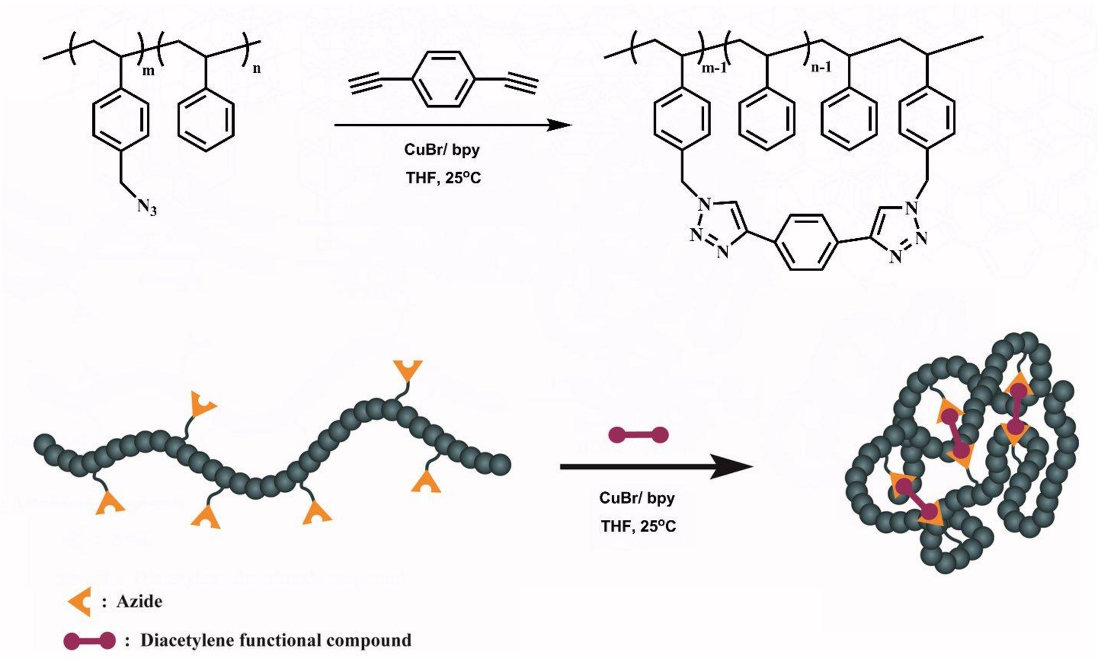
[b] Determined gravimetrically.

[c] Determined from GPC measurements based on polystyrene standards.

[d] Calculated by using ^{1}H-NMR spectra.

In the final step, intramolecular cross-linking reaction was performed via Cu(I)-catalyzed click reaction at room temperature. Solutions of azide functionalized copolymers (PS-N_3) were added dropwise to the diacetylene containing solutions and CuBr/bpy catalyzed triazole formation was accomplished between the azides of PS-N_3 and diacetylene functions of DPD or DEB (Scheme 4.2). The resulting polymers were recovered quantitatively by precipitation in methanol and characterized by gel permeation chromatography (GPC), FT-IR and ^{1}H NMR spectroscopy. The results are summarized in Table 4.2. As can be seen, the molecular weights of azide functionalized polymers significantly decreased after click reaction which could be attributed to the intramolecular cross-linking. Intramolecular click cycloaddition leads to an intramolecular collapse of the linear chains.

The cyclic polymers formed this way exhibit significant reduction in their apparent molecular weight (40–50%) with no significant change in polydispersity and hydrodynamic volume (Table 4.2). In order to investigate the structural effect on hydrodynamic volumes of the polymers, a second set of polymers was prepared by using two different click agents with different chain structures, DEB and DPD, (Table 4.2, Run 2 and 3). The results showed that decrease in hydrodynamic volume of the polymer clicked with DPD was around 50% whereas with DEB this value was around 30%. The relatively lower decrease in the hydrodynamic volume obtained in the case of DEB may be attributed to its rigid structure arising from the central aromatic ring. Moreover, cyclic polymers obtained by using DEB was found to be slightly soluble in THF and DMF.



Scheme 4.2 : Schematic representation of the preparation of single-chain cross-linked polymer by intramolecular click cycloaddition.

Table 4.2 : Characteristics of polymers obtained after azidation and click reactions.

			After Azidation Reaction			**After Click Reaction**	
Run	**Precursor polymer**	**Click agent**	**%N$_3$**	**$M_{n,GPC}$ (g·mol^{-1})**	**M_w/M_n**	**$M_{n,GPC}$ (g·mol^{-1})**	**M_w/M_n**
1	**P(S-co-CMS)-1**	DEB	22	93600	2.3	44300	2.7
2	**P(S-co-CMS)-2**	DPD	18	65800	3.5	32200	3.1
3	**P(S-co-CMS)-2**	DEB	18	65800	3.5	45700	1.5
4	**P(S-co-CMS)-3**	DEB	21	74500	1.5	29800	2.3

One of the cyclic polymers (Table 4.2, Run 1) was chosen in order to confirm the occurrence of intramolecular click reaction spectroscopically. As can be seen from Figure 4.1 where ^{1}H-NMR spectra of the polymers before and after click reaction are presented, the methylene protons adjacent to the azido group at 4.2 ppm disappeared and the new methylene protons next to the triazole ring appeared at 5.3 ppm. FT-IR spectral investigation also confirms the successful click reaction. The band corresponding to the $-N_3$ group at 2095 cm^{-1} completely disappeared after click reaction (Figure 4.2).

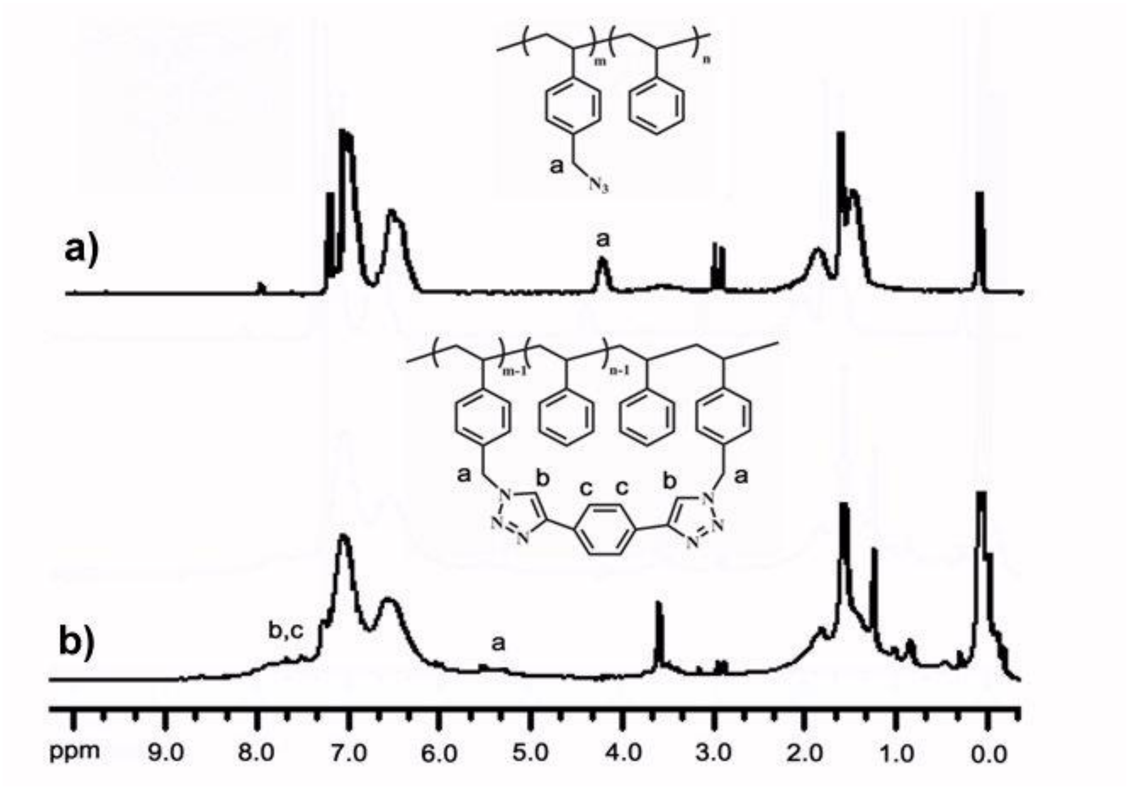


Figure 4.1: ^{1}H NMR spectra of a) azide functionalized polymer and b) cyclic polymer in $CDCl_3$.

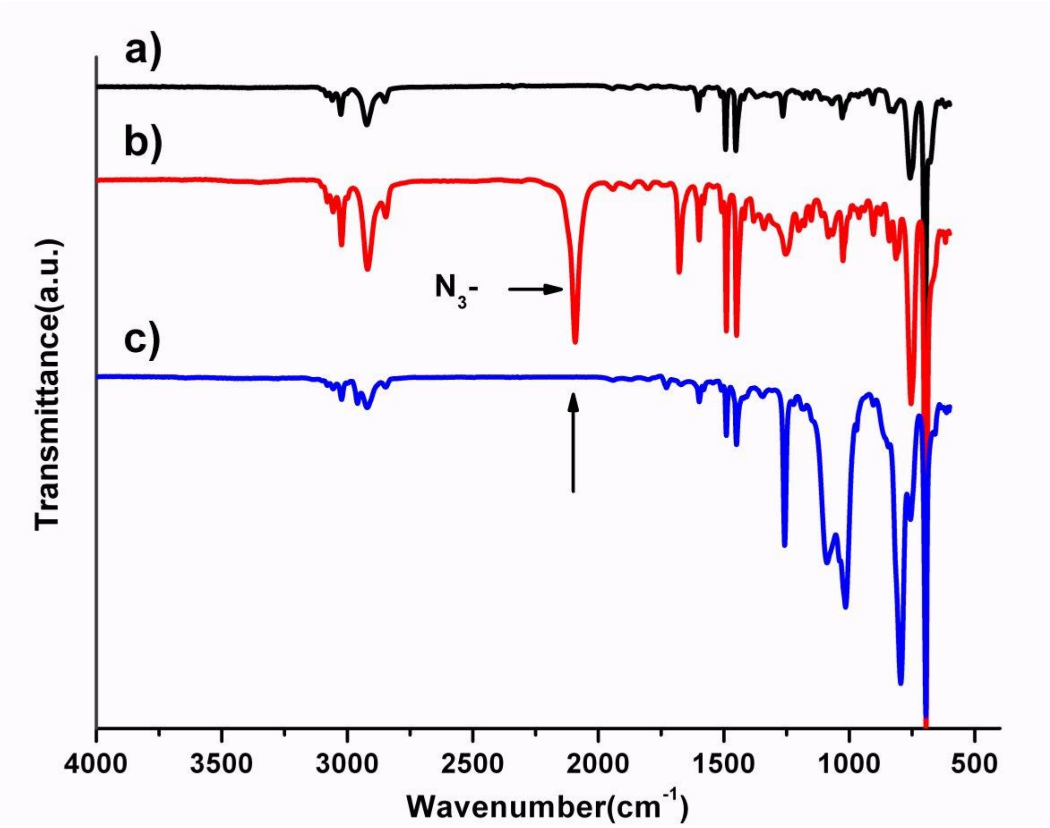


Figure 4.2: FT-IR spectra of a) P(S-*co*-CMS)-1, b) PS-N_3 and c) cyclic polymer.

The GPC traces of P(S-*co*-CMS)-1 and corresponding cyclic polymer obtained after click reaction are shown in Figure 4.3. Expectedly, the molecular weight of cyclic polymer is lower than that of the corresponding azide functional precursor.

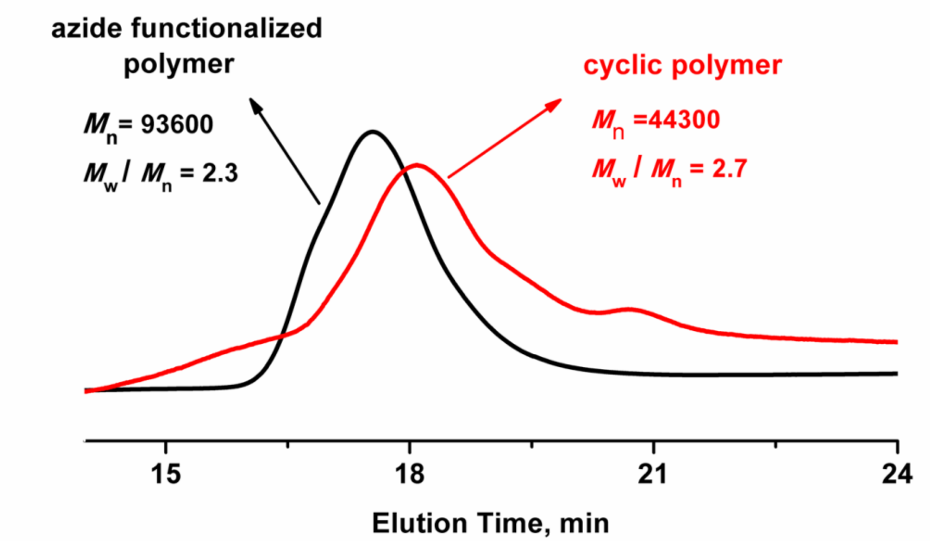


Figure 4.3: GPC traces of azide functionalized polymer and cyclic polymer.

The glass transition temperatures of PS-N_3 and cyclic polymer were measured by differential scanning calorimetry (DSC) (Figure 4.4). The T_g value of PS-N_3 shifted from 95°C to 132°C after intramolecular click reaction due to the decreased segmental chain mobility. Previously, similar shifts were observed in the glass transition temperatures of copolyesters after self-crosslinking reactions [12].

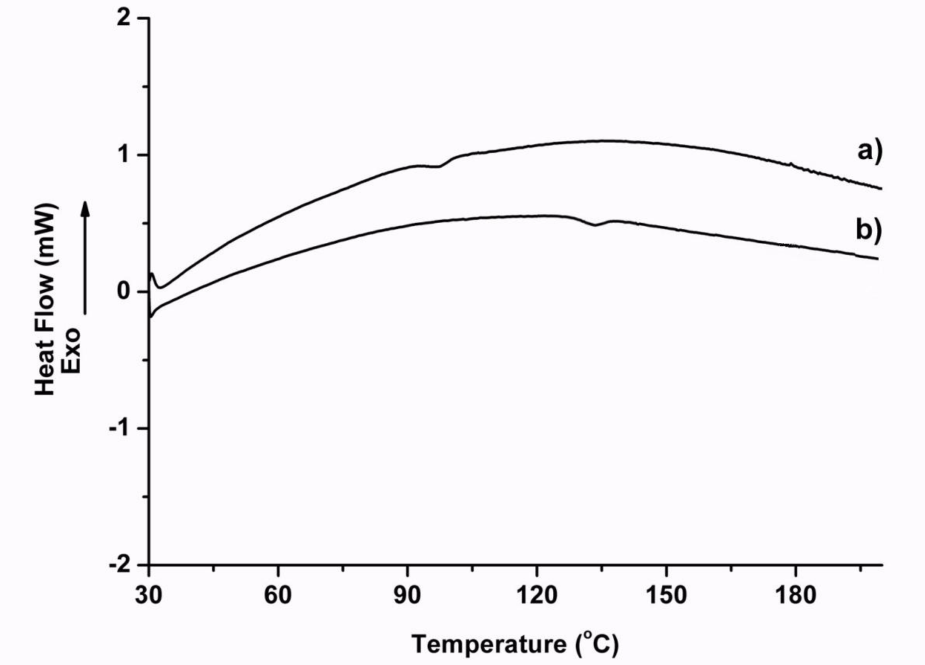


Figure 4.4: DSC thermograms of a) azide functionalized polymer and b) cyclic polymer.

Figure 4.5, shows the shear rate dependent viscosities of P(S-*co*-CMS)-1, PS-N_3 analogue and corresponding cyclic polymer. The data were obtained by using the same concentrations (4.2×10^{-7} mol·L^{-1}) of the samples. As expected, a clear change was observed in the viscosities of P(S-*co*-CMS)-1, PS-N_3 and cyclic polymer. The decrease of viscosity after cyclic polymer formation can be ascribed to the particle-like behavior of the polymer rather than a linear macromolecule.

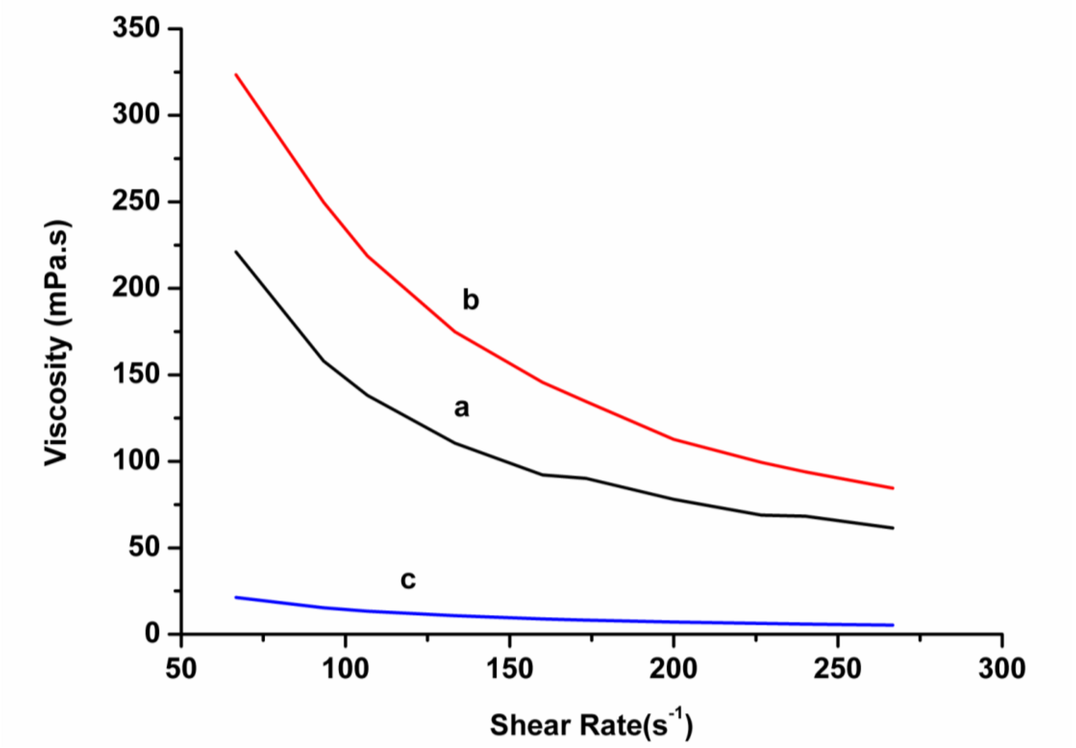


Figure 4.5: Shear rate dependence of viscosity for a) P(S-*co*-CMS), b) azide functionalized polymer and c) cyclic polymer at 25°C.

5. CONCLUSIONS AND RECOMMENDATIONS

In this thesis, demonstrated the use of click reaction as a versatile synthetic route to prepare cyclic polymers. Azide functionalized copolymers were intramolecularly cross-linked with appropriate diacetylene functional compounds in ultra-dilute conditions via click chemistry approach. The structures of obtained particle-like structures have been fully characterized ^{1}H NMR, FT-IR, GPC and DSC.

REFERENCES

[1] **Hawker, C. J., Hedrick, J. L., Miller, R. D. and Volksen, W.** (2000). Supramolecular approaches to nanoscale dielectric foams for advanced microelectronic devices, *Mrs Bull.*, **25**, 54-58.

[2] **Yang, S., Mirau, P. A., Pai, C. S., Nalamasu, O., Reichmanis, E., Lin, E.K.,Lee, H.J., Gidley D. W. and Sun, J. N.** (2001). Molecular templating of nanoporous ultralow dielectric constant (approximate to 1.5) organosilicates by tailoring the microphase separation of triblock copolymers, *Chem. Mater.*,**13**, 2762-2764.

[3] **Guillaudeu, S. J., Fox, M. E., Haidar, Y. M., Dy, E. E., Szoka, F. C. and Frechet, J. M. C.** (2008). PEGylated Dendrimers with Core Functionality for Biological Applications, *Bioconjugate Chem.*, **19**, 461-469.

[4] **Liu, J. Q., Zhang, Q., Remsen, E. E. and Wooley, K. L.** (2001). Nanostructured materials designed for cell binding and transduction, *Biomacromolecules,* **2**, 362-368.

[5] **Motornov, M., Roiter, Y., Tokarev, I. and Minko, S.** (2010). Stimuliresponsive nanoparticles, nanogels and capsules for integrated multifunctional intelligent systems, *Prog. Polym. Sci.*, **35**, 174-211.

[6] **Sudeep, P. K., Page, Z. and Emrick, T.** (2008). PEGylated silicon nanoparticles: synthesis and characterization, *Chem. Commun.*, 6126-6127.

[7] **Baoum, A., Dhillon, N., Buch, S. and Berkland, C.** (2010). Cationic surface modification of PLG nanoparticles offers sustained gene delivery to pulmonary epithelial cells, *J. Pharm. Sci.*, **99**, 2413-2422.

[8] **O'Reilly, R. K., Joralemon, M. J., Hawker, C. J. and Wooley, K. L.** (2006). Facile syntheses of surface-functionalized micelles and shell cross-linked nanoparticles, *J. Polym. Sci. Part A: Polym. Chem.*, **44**, 5203-5217.

[9] **van der Ende, A., Croce, T., Hamilton, S., Sathiyakumar, V. and Harth, E.** (2009). Tailored polyester nanoparticles: post-modification with dendritic transporter and targeting units via reductive amination and thiol-ene chemistry, *Soft Matter*, **5**, 1417-1425.

[10] **Mackay, M. E., Tuteja, A., Duxbury, P. M., Hawker, C. J., Van Horn, B., Guan, Z. B., Chen, G. H. and Krishnan, R. S.** (2006). General strategies for nanoparticle dispersion, *Science*, **311**, 1740-1743.

[11] **Harth, E., Van Horn, B., Lee, V. Y., Germack, D. S., Gonzales, C. P., Miller, R. D., and Hawker, C. J.** (2002). A facile approach to architecturally defined nanoparticles via intramolecular chain collapse,*J. Am. Chem. Soc.*, **124**, 8653-8660.

[12] **Mecerreyes, D., Lee, V., Hawker, C. J., Hedrick, J. L., Wursch, A., Volksen, W., Magbitang, T., Huang, E. and Miller, R. D.** (2001). A novel approach to functionalized nanoparticles: Self-crosslinking of macromolecules in ultradilute solution, *Adv. Mater.*, **13**, 204-208.

[13] **Croce, T. A., Hamilton, S. K., Chen, M. L., Muchalski, H. and Harth, E.** (2007). Alternative o-chinodimethane crosslinking precursors for intramolecular chain collapse nanoparticles, *Macromolecules*, **40**, 6028-6031.

[14] **de Luzuriaga, A. R., Ormategui, N., Grande, H. J., Odriozola, I., Pomposo, J. A. and Loinaz, I.** (2008). Intramolecular Click Cycloaddition: An Efficient Room-Temperature Route towards Bioconjugable Polymeric Nanoparticles, *Macromol. Rapid Commun.*, **29**, 1156-1160.

[15] **Foster, E. J., Berda, E. B. and Meijer, E. W.** (2009). Metastable supramolecular polymer nanoparticles via intramolecular collapse of single polymer chains, *J. Am. Chem. Soc.*, **131**, 6964-6966.

[16] **Jiang, J. and Thayumanavan, S.** (2005). Synthesis and Characterization of Amine- Functionalized Polystyrene. Nanoparticles, *Macromolecules*, **38**, 5886-5891.

[17] **Cherian, A. E., Sun, F. C., Sheiko, S. S. and Coates, G. W.** (2007). Formation of Nanoparticles by Intramolecular Cross-Linking: Following the Reaction Progress of Single Polymer Chains by Atomic Force Microscopy, *J. Am. Chem. Soc.*, **129**, 11350-11351.

[18] **Beck, J. B., Killops, K. L., Kang, T., Sivanandan, K., Bayles, A., Mackay, M. E., Wooley, K. L. and Hawker, C. J.** (2009). Facile Preparation of Nanoparticles by Intramolecular Cross-Linking of Isocyanate Functionalized Copolymers, *Macromolecules*, **42**, 5629-5635.

[19] **Chen, D. Y., Peng, H. S. and Jiang, M.** (2003). A novel one-step approach to core-stabilized nanoparticles at high solid contents, *Macromolecules*, **36**, 2576-2578.

[20] **Huisgen, R.** (1984). 1,3-Dipolar Cycloaddition Chemistry, *Wiley*, New York, **1**, 1-176.

[21] **Kolb, H. C., Finn, M. G. and Sharpless, K. B.** (2001). Click Chemistry: Diverse Chemical Function from a Few Good Reactions, *Angew. Chem. Int. Edit.*, **40**, 2004-2021.

[22] **Rostovtsev, V. V., Green, L. G., Fokin, V. V. and Sharpless, K. B.** (2002). A Stepwise Huisgen Cycloaddition Process: Copper(I)-Catalyzed Regioselective Ligation of Azides and Terminal Alkynes, *Angew. Chem. Int. Edit.*, **41**, 2596-2599.

[23] **Tornoe, C. W., Christensen, C. and Meldal, M.** (2002). Peptidotriazoles on Solid Phase: [1,2,3]-Triazoles by Regiospecific Copper(I)-Catalyzed 1,3-Dipolar Cycloadditions of Terminal Alkynes to Azides, *J. Org. Chem.*, **67**, 3057-3064.

[24] **Akat, H., Gacal, B., Balta, D. K., Arsu, N. and Yagci, Y.** (2010). Poly(ethylene glycol)-thioxanthone prepared by Diels–Alder click chemistry as one-component polymeric photoinitiator for aqueous free-radical polymerization, *J. Polym. Sci. Part A: Polym. Chem.*, **48**, 2109-2114.

[25] **Gacal, B., Durmaz, H., Tasdelen, M. A., Hizal, G., Tunca, U., Yagci, Y. and Demirel, A. L.** (2006). Anthracene−Maleimide-Based Diels−Alder “Click Chemistry” as a Novel Route to Graft Copolymers, *Macromolecules*, **39**, 5330-5336.

[26] **Kwart, H. and King, K.** (1968). The reverse Diels-Alder or retrodiene reaction, *Chem. Rev.*, **68**, 415-447.

[27] **Gress, A., Volkel, A. and Schlaad, H.** (2007). Thio-click modification of poly[2-(3- butenyl)-2-oxazoline], *Macromolecules,* **40**, 7928-7933.

[28] **Uygun, M., Tasdelen, M. A. and Yagci, Y.** (2010). Influence of Type of Initiation on Thiol-Ene "Click" Chemistry, *Macromol. Chem. Phys.*, **211**, 103-110.

[29] **Lutz, J. F., Borner, H. G. and Weichenhan, K.** (2005). A versatile method for preparing end-functional polymers, *Macromol. Rapid Commun.*, **26**, 514-518.

[30] **Liu, Q. C. and Chen, Y. M.** (2006). Synthesis of well-defined macromonomers by the combination of atom transfer radical polymerization and a click reaction, *J. Polym. Sci. Part A: Polym. Chem.*, **44**, 6103-6113.

[31] **Vogt, A. P. and Sumerlin, B. S.** (2006). An efficient route to macromonomers via ATRP and click chemistry, *Macromolecules,* **39**, 5286-5292.

[32] **Gacal, B., Akat, H., Balta, D. K., Arsu, N. and Yagci, Y.** (2008). Synthesis and Characterization of Polymeric Thioxanthone Çift tıklayın Tepkiler üzerinden Photoinitatiors Photoinitatiors via Double Click Reactions, *Macromolecules,* **41**, 2401-2405.

[33] **Temel, G., Aydogan, B., Arsu, N. and Yagci, Y.** (2009). Synthesis and Characterization of One-Component Polymeric Photoinitiator by Simultaneous Double Click Reactions and Its Use in Photoinduced Free Radical Polymerization, *Macromolecules,* **42**, 6098-6106.

[34] **Durmaz, H., Dag, A., Altintas, O., Erdogan, T., Hizal, G. and Tunca, U.** (2007). One-Pot Synthesis Of ABC Type Triblock Copolymers Via In Situ Click [3+2] And Diels-Alder [4+2] Reactions, *Macromolecules,* **40**, 191-198.

[35] **Kluger, C. and Binder, W. H.** (2007). Functionalized Poly(oxanorbornene)-block-Copolymers: Preparation via ROMP/click-Methodology, *J. Polym. Sci. Part A: Polym. Chem.,* **45**, 485-499.

[36] **Quemener, D., Davis, T. P., Barner-Kowollik, C. and Stenzel, M. H.** (2006). RAFT and Click Chemistry: A Versatile Approach to Well-Defined Block Copolymers, *Chem. Commun.,* 5051-5053.

[37] **Ladmiral, V., Mantovani, G., Clarkson, G. J., Cauet, S., Irwin, J. L. and Haddleton, D. M.** (2006). Synthesis of Neoglycopolymers by a Combination of "Click Chemistry" and Living Radical Polymerization, *J. Am. Chem. Soc.*, **128**, 4823-4830.

[38] **Luxenhofer, R. and Jordan, R.** (2006). Click Chemistry with Poly(2-oxazoline)s, *Macromolecules*, **39**, 3509-3516.

[39] **Sumerlin, B. S., Tsarevsky, N. V., Louche, G., Lee, R. Y. and Matyjaszewski, K.** (2005). Highly Efficient "Click" Functionalization of Poly(3-azidopropyl methacrylate) Prepared by ATRP, *Macromolecules,* **38**, 7540-7545.

[40] **Durmaz, H., Dag, A., Gursoy, D., Demirel, A. L., Hizal G. and Tunca, U.** (2010). Multiarm Star Block Terpolymers via Sequential Double Click Reactions, *J. Polym. Sci. Part A: Polym. Chem.*, **48**, 1557-1564.

[41] **Gao, H. F. and Matyjaszewski, K.** (2006). Synthesis of star polymers by a combination of atrp and the "click" coupling method, *Macromolecules*, **39**, 4960-4965.

[42] **Fu, Q., Wang, G. W., Lin, W. C. and Huang, J. L.** (2009). One-Pot Preparation of 3-Miktoarm Star Terpolymers via “Click Chemistry”and Atom Transfer Nitroxide Radical Coupling Reaction, *J. Polym. Sci. Part A: Polym. Chem.*, **47**, 986-990.

[43] **Gozgen, A., Dag, A., Durmaz, H., Sirkecioglu, O., Hizal, G. and Tunca, U.** (2009). ROMP-NMP-ATRP Combination for the Preparation of 3-Miktoarm Star Terpolymer via Click Chemistry, *J. Polym. Sci. Part A: Polym. Chem.*, **47**, 497-504.

[44] **Gungor, E., Hizal, G. and Tunca, U.** (2009). One-pot double click Reactions for the preparation of H-shaped ABCDE type quintopolymer, *J. Polym. Sci. Part A: Polym. Chem.*, **47**, 3409-3419.

[45] **Franc, G. and Kakkar, A.** (2008). Dendrimer Design Using Cu(I)-Catalyzed Alkyne-Azide Click Chemistry, *Chem. Commun.*, 5267.5276.

[46] **Wu, P., Feldman, A. K., Nugent, A. K., Hawker, C. J., Scheel, A., Voit, B., Pyun, J., Frechet, J. M. J., Sharpless, K. B. and Fokin, V. V.** (2004). Efficiency and fidelity in a click-chemistry route to triazole dendrimers by the copper(I)-catalyzed ligation of azides and alkynes, *Angew. Chem. Int. Edit.*, **43**, 3928-3932.

[47] **Xiong, X. Q.** (2010). Thiol-Ene Click Chemistry, *Chinese J. Org. Chem.*, **30**, 307-310.

[48] **Helms, B., Mynar, J. L., Hawker, C. J. and Frechet, J. M. J.** (2004). Dendronized Linear Polymers Via "Click Chemistry, *J. Am. Chem. Soc.*, **126**, 15020-15021.

[49] **Mynar, J. L., Choi, T. L., Yoshida, M., Kim, V., Hawker, C. J. and Frechet, J. M. J.** (2005). Doubly-dendronized polymers were synthesized by grafting polybenzyl ether dendrons onto a poly(hydroxy) styrene polymer with polyaliphatic esters, *Chem. Commun.*, 5169-5171.

[50] **Laurent, B. A. and Grayson**, **S. M.** (2006). An efficient route to well-defined macrocyclic polymers via "click" cyclization, *J. Am. Chem. Soc.***,** **128**, 4238-4239.

[51] **Misaka, H., Kakuchi, R., Zhang, C. H., Sakai, R., Satoh, T. and Kakuchi, T.** (2009). Synthesis of Well-Defined Macrocyclic Poly(delta-valerolactone) by "Click Cyclization", *Macromolecules*, **42**, 5091-5096.

[52] **Ergin, M., Kiskan, B., Gacal, B. and Yagci, Y.** (2007). Thermally curable polystyrene via click chemistry, *Macromolecules*, **40**, 4724-4727.

[53] **Kiskan, B., Demiray, G. and Yagci, Y.** (2008). Thermally curable polyvinylchloride via click chemistry, *J. Polym. Sci. Part A: Polym. Chem.*, **46**, 3512-3518.

[54] **Kukut, M., Kiskan, B. and Yagci, Y.** (2009). Self-curable benzoxazine functional polybutadienes synthesized by click chemistry, *Des. Monomers Polym.*, **12**, 167-176.

[55] **Johnson, J. A., Lewis, D. R., Az, D., Finn, M. G., Koberstein, J. T. and Turro, N. J.** (2006). Synthesis of Degradable Model Networks via ATRP and Click Chemistry, *J. Am. Chem. Soc.*, **128**, 6564-6565.

[56] **Malkoch, M., Vestberg, R., Gupta, N., Mespouille, L., Dubois, P., Mason, A.F., Hedrick, J. L., Liao, Q., Frank, C. W., Kingsbury, K. and Hawker, C. J.** (2006). Synthesis of well-defined hydrogel networks using Click chemistry, *Chem. Commun.*, 2774-2776.

[57] **Oria, L., Aguado, R., Pomposo, J. A. and Colmenero, J.** (2010). A Versatile "Click" Chemistry Precursor of Functional Polystyrene Nanoparticles, *Adv. Mater.*, **22**, 3038-3041.

[58] **Binder, W. H. and Sachsenhofer, R.** (2007). Click Chemistry in Polymer and Materials Science, *Macromol. Rapid Commun.*, **28**, 15-24.

[59] **Lutz, J. F.** (2007). 1,3-Dipolar Cycloadditions of Azides and Alkynes: a Universal Ligation Tool in Polymer and Materials Science, *Angew. Chem. Int. Edit.*, **46**, 1018-1025.

[60] **Golas, P. L. and Matyjaszewski, K.** (2010). Marrying click chemistry with polymerization: expanding the scope of polymeric materials, *Chem. Soc. Rev.*, **39**, 1338-1354.

[61] **Sumerlin, B. S. and Vogt, A. P.** (2010). Macromolecular Engineering through Click Chemistry and Other Efficient Transformations, *Macromolecules*, **43**, 1-13.

[62] **Fournier, D., Hoogenboom, R. and Schubert, U. S.** (2007). Clicking polymers: a straightforward approach to novel macromolecular architectures, *Chem. Soc. Rev.*, **36**, 1369-1380.

[63] **Moses, J. E. and Moorhouse, A. D.** (2007). The growing applications of click chemistry, *Chem. Soc. Rev.*, **36**, 1249-1262.

[64] **Ates, S., Durmaz, Y. Y., Torun, L. and Yagci, Y.** (2010). Synthesis and Characterization of Polystyrene Possessing Triptycene Units in the Main Chain by Combination of ATRP and Click Chemistry Processes, *J. Macromol. Sci. Part A: Pure Appl. Chem.*, **47**, 809-815.

[65] **Ebewele, R. O.** (2000). Polymer Science and Technology, *CRC Press LLC*, Florida, 25-51.

[66] **Odian, G. G.** (2004). Principles of Polymerization, *John Wiley & Sons*, 36-31.

[67] **Kolb, H. C., Finn, M. G. And Sharpless, K. B.** (2001). Click Chemistry: Diverse chemical function from a few good reactions, *Angewandte Chemie-International Edition*, **40**, 2004-2021.

[68] **Rostovtsev, V. V., Green, L. G., Fokin, V. V. And Sharpless, K. B.** (2002). A stepwise huisgen cycloaddition process : Copper(i)-catalyzed regioselective "ligation" of azides and terminal alkynes, *Angewandte Chemie-International Edition*, **41**, 2596-2599.

[69] **Tornoe, C. W., Christensen, C. And Meldal, M.** (2002). Peptidotriazoles on solid phase : 1,2,3-triazoles by regiospecific copper(i)-catalyzed 1,3-dipolar cycyloaddtions of terminal alkynes to azidez, *Journal of Organic Chemistry*, **67**, 3057-3064.

[70] **Meldal, M.** (2008). Polymer "Clicking" by CuAAC Reactions, *Macromol. Rapid Commun.*, **29**, 1016-1051.

[71] **Kolb, H. C. and Sharpless, K. B.** (2003). The growing impact of click chemistry on drug discovery, *Drug Discovery Today*, **8**, 1128-1137.

[72] **Diels, O. and Alder, K.** (1928). Sythesen in der hydroaromatischen Reihe, *Liebigs Ann. Chem.*, **460**, 98-122.

[73] **Sauer, J. and Sustmann, R.** (1980). Mechanistic aspect of Diels-Alder reactions : A Critical Survey, *Angew. Chem. Int. Ed.*, **19**, 779-807.

[74] **Nicolaou, K. C., Snyder, S. A., Montagnon, T. and Vassilikogiannakis, G.** (2002). The Diels-Alder Reaction in Total Synthesis, *Angew. Chem. Int. Ed.*, **41**, 1668-1698.

[75] **Dondoni, A.** (2008), The Emergence of Thiol-Ene Coupling as a Click Process for Materials and Bioorganic Chemistry, *Angewandte Chemie-International Edition*, **47**, 8995-8997.

[76] **Hoyle, C. E. and Bowman, C. N.** (2010). Thiol-Ene Click Chemistry, *Angewandte Chemie-International Edition*, **49**, 1540-1573.

[77] **Morgan, C. R., Magnotta, F. and Ketley, A.D.** (1977), Thiol-ene photocurable polymers, *Journal of Polymer Science Part A-Polymer Chemistry*, **15**, 627-645.

[78] **Griesbau, K.** (1970). Problems and possibilities of free radical addition of thiols to unsaturated compounds, *Angewandte Chemie-International Edition*, **9**, 273-287.

[79] **Rissing, C. and Son, D. Y.** (2008). The Thiol-ene Reaction for the Synthesis of Multifunctional Branched Organosilanes, *Organometallics*, **27**, 5394-5397.

[80] **Bhattacharya, A., Rawlins, J. W. and Ray, P.** (2009). Polymer Grafting and Crosslinking, *John Wiley & Sons.*,315-318.

[81] **Wang, W., Lu, X. G., Xie, X.** (2008) Evaluation of Intra-Molecular Cross-Linked Polymers, *AAPG Joint Meeting*, USA, http://www.onepetro.org/mslib/app/Preview

[82] **Manna, S., Mandal, A. and Nandi, K.** (2010). Polymer Science Unit, *Indian Association for the CultiVation of Science*, JadaVpur, Calcutta 700 032.

CURRICULUM VITAE

Name Surname:	Halime CENGİZ
Place and Date of Birth:	Şebinkarahisar/GİRESUN - 02.08.1983
Address:	İstanbul Teknik Üniversitesi, Fen Edebiyat Fakültesi, Kimya Bölümü, 34469, Maslak, İstanbul
E-Mail:	halime_cengiz@yahoo.com
B.Sc.:	Middle East Technical University, Chemistry

PUBLICATIONS/PRESENTATIONS ON THE THESIS

- **Cengiz H.**, Aydogan B., Ates S., Acikalin E., Yagci Y., 2011, Intramolecular Cross-linking of Polymers Using Difunctional Acetylenes via Click Chemistry, *Designed Monomers and Polymers*, 2011, 14, 69-78.