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Uses of polymers in today life & future trends

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Abstract: **In recent years, there has been a marked increase in interest in biodegradable materials for use in packaging, agriculture, medicine, and other areas. In particular, biodegradable polymer materials (known as biocomposites) are of interest. Polymers form the backbones of plastic materials, and are continually being employed in an expanding range of areas. As a result, many researchers are investing time into modifying traditional materials to make them more user-friendly, and into designing novel polymer composites out of naturally occurring materials. A number of biological materials may be incorporated into biodegradable polymer materials, with the most common being starch and fiber extracted from various types of plants. The belief is that biodegradable polymer materials will reduce the need for synthetic polymer production (thus reducing pollution) at a low cost, thereby producing a positive effect both environmentally and economically. This paper is intended to provide a brief outline of work that is under way in the area of biodegradable polymer research and development, the scientific theory behind these materials, areas in which this research is being applied, and future work that awaits.**

Keywords**: Polymer, classification, structure, today life & future trends**

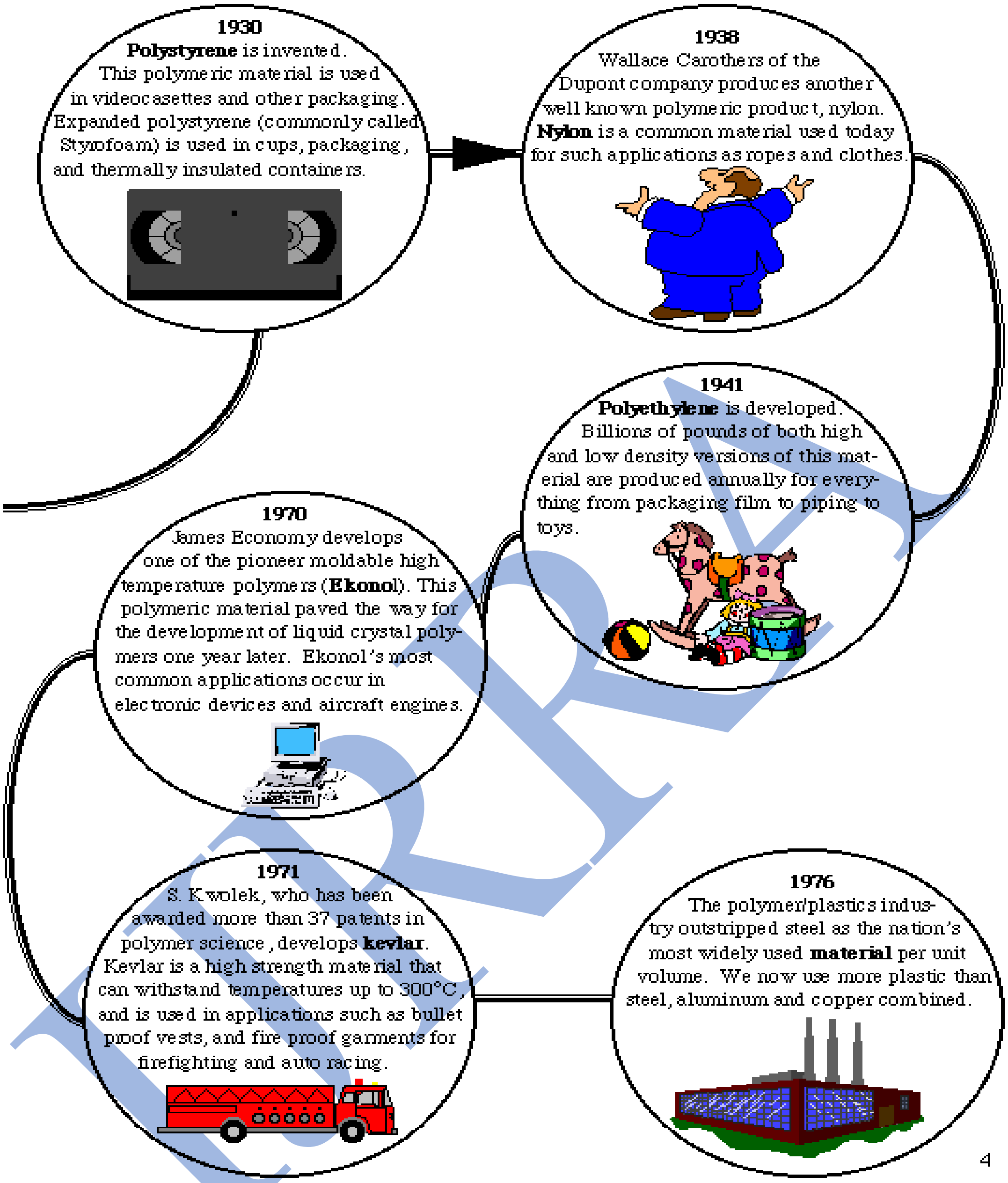
I. INTRODUCTION

Many polymers exist in nature. Among these are silk, cotton, starch, sand, and asbestos, as well as the incredibly complex polymers known as RNA (ribonucleic acid) and DNA (deoxyribonucleic acid), which hold genetic codes. The polymers discussed in this essay, however, are primarily of the synthetic kind. Artificial polymers include such plastics (defined below) as polyethylene, styrofoam, and Saran wrap; fibers such as nylon, Dacron (polyester), and rayon; and other materials such as Formica, Teflon, and PVC pipe.

Polymers are made up of many many molecules all strung together to form really long chains (and sometimes more complicated structures, too). What makes polymers so fun is that how they act depends on what kinds of molecules they're made up of and how they're put together. The properties of anything made out of polymers really reflect what's going on at the ultra-tiny (molecular) level. So, things that are made of polymers look, feel, and act depending on how their atoms and molecules are connected, as well as which ones we use to begin with! Some are rubbery, like a bouncy ball, some are sticky and gooey, and some are hard and tough, like a skateboard.

As noted earlier, most polymers are formed from monomers either of hydrocarbon or hydro-carbon derivatives. The most basic synthetic monomer is ethylene (C_2H_4), a name whose-ene ending identifies it as an alkene, a hydrocarbon formed by double bonds between carbon atoms. Another alkene hydrocarbon monomer is butadiene, whose formula is C_4H_6. This is an example of the fact that the formula of a compound does not tell the whole story: on paper, the difference between these two appears to be merely a matter of two extra atoms each of carbon and hydrogen. In fact, butadiene's structure is much more complex.

Still more complex is styrene, which includes a benzene ring. Several other monomers involve other elements: chloride, in vinyl chloride; nitrogen, in acrylonitrile; and fluorine, in tetrafluoroethylene. It is not necessary, in the present context, to keep track of all of these substances, which in any case represent just some of the more prominent among a wide variety of synthetic monomers. A good high-school or college chemistry textbook (either general chemistry or organic chemistry) should provide structural representations of these common monomers. Such representations will show, for instance, the vast differences between purely hydrocarbon monomers such as ethylene, propylene, styrene, and butadiene. When combined into polymers, the monomers above form the basis for a variety of useful and familiar products. Once the carbon double bonds in tetrafluoroethylene (C_2F_4) are broken, they form the polymer known as Teflon, used in the coatings of cooking utensils, as well as in electrical insulation and bearings. Vinyl chloride breaks its double bonds to form polyvinyl chloride, better known as PVC, a material used for everything from plumbing pipe to toys to Saran wrap. Styrene, after breaking its double bonds, forms polystyrene, used in containers and thermal insulation.



1930
Polystyrene is invented. This polymeric material is used in videocasettes and other packaging. Expanded polystyrene (commonly called Styrofoam) is used in cups, packaging, and thermally insulated containers.

1938
Wallace Carothers of the Dupont company produces another well known polymeric product, nylon. **Nylon** is a common material used today for such applications as ropes and clothes.

1941
Polyethylene is developed. Billions of pounds of both high and low density versions of this material are produced annually for everything from packaging film to piping to toys.

1970
James Economy develops one of the pioneer moldable high temperature polymers (**Ekonol**). This polymeric material paved the way for the development of liquid crystal polymers one year later. Ekonol's most common applications occur in electronic devices and aircraft engines.

1971
S. Kwolek, who has been awarded more than 37 patents in polymer science, develops **kevlar**. Kevlar is a high strength material that can withstand temperatures up to 300°C, and is used in applications such as bullet proof vests, and fire proof garments for firefighting and auto racing.

1976
The polymer/plastics industry outstripped steel as the nation's most widely used **material** per unit volume. We now use more plastic than steel, aluminum and copper combined.

Figure 1 History of Polymers

Many inorganic polymers also are found in nature, including diamond and graphite. Both are composed of carbon. In diamond, carbon atoms are linked in a three-dimensional network that gives the material its hardness. In graphite, used as a lubricant and in pencil "leads," the carbon atoms link in planes that can slide across one another

II. SCIENTIFIC PRINCIPLES

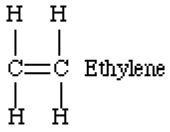
The field of polymers is so vast and the applications so varied, that it is important to understand how polymers are made and used. Since there are over 60,000 different plastics vying for a place in the market, knowledge of this important field can truly enrich our appreciation of this wonder material. Companies manufacture over 30 million tons of plastics each year, and spend large sums on research, development, and more efficient recycling methods. Below we learn some of the scientific principles involved in the production and processing of these fossil fuel derived materials known as polymers.

Polymerization Reactions

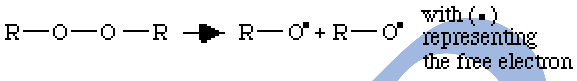
The chemical reaction in which high molecular mass molecules are formed from monomers is known as polymerization. There are two basic types of polymerization, chain-reaction (or addition) and step-reaction (or condensation) **polymerization**.

Chain-Reaction Polymerization

One of the most common types of polymer reactions is chain-reaction (addition) polymerization. This type of polymerization is a three step process involving two chemical entities. The first, known simply as a monomer, can be regarded as one link in a polymer chain. It initially exists as simple units. In nearly all cases, the monomers have at least one carbon-carbon double bond. Ethylene is one example of a monomer used to make a common polymer.



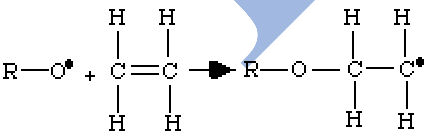
The other chemical reactant is a catalyst. In chain-reaction polymerization, the catalyst can be a free-radical peroxide added in relatively low concentrations. A free-radical is a chemical component that contains a free electron that forms a covalent bond with an electron on another molecule. The formation of a free radical from an organic peroxide is shown below:



In this chemical reaction, two free radicals have been formed from the one molecule of R_2O_2. Now that all the chemical components have been identified, we can begin to look at the polymerization process.

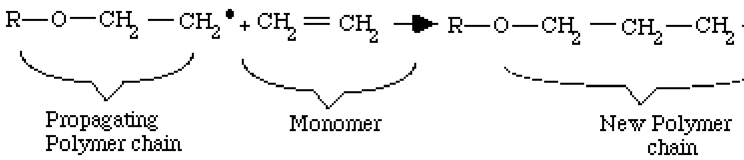
Step 1: Initiation

The first step in the chain-reaction polymerization process, initiation, occurs when the free-radical catalyst reacts with a double bonded carbon monomer, beginning the polymer chain. The double carbon bond breaks apart, the monomer bonds to the free radical, and the free electron is transferred to the outside carbon atom in this reaction.



Step 2: Propagation

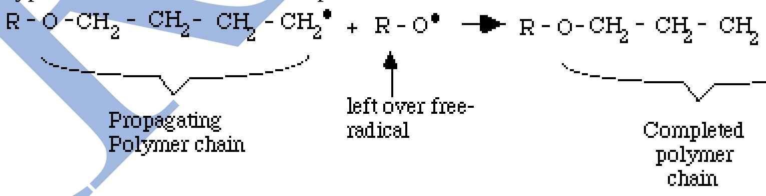
The next step in the process, propagation, is a repetitive operation in which the physical chain of the polymer is formed. The double bond of successive monomers is opened up when the monomer is reacted to the reactive polymer chain. The free electron is successively passed down the line of the chain to the outside carbon atom.

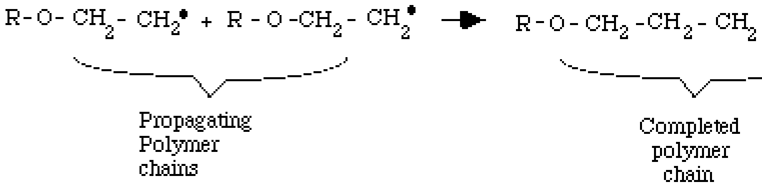


This reaction is able to occur continuously because the energy in the chemical system is lowered as the chain grows. Thermodynamically speaking, the sum of the energies of the polymer is less than the sum of the energies of the individual monomers. Simply put, the single bounds in the polymeric chain are more stable than the double bonds of the monomer.

Step 3: **Termination**

Termination occurs when another free radical (R-O$\cdot$), left over from the original splitting of the organic peroxide, meets the end of the growing chain. This free-radical terminates the chain by linking with the last $CH_2\cdot$ component of the polymer chain. This reaction produces a complete polymer chain. Termination can also occur when two unfinished chains bond together. Both termination types are diagrammed below. Other types of termination are also possible.

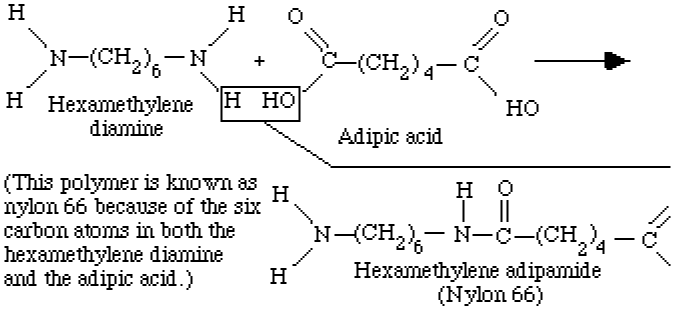




This exothermic reaction occurs extremely fast, forming individual chains of polyethylene often in less than 0.1 second. The polymers created have relatively high molecular weights. It is not unusual for branches or cross-links with other chains to occur along the main chain.

Step-Reaction Polymerization

Step-reaction (condensation) polymerization is another common type of polymerization. This polymerization method typically produces polymers of lower molecular weight than chain reactions and requires higher temperatures to occur. Unlike addition polymerization, step-wise reactions involve two different types of di-functional monomers or end groups that react with one another, forming a chain. Condensation polymerization also produces a small molecular by-product (water, HCl, etc.). Below is an example of the formation of Nylon 66, a common polymeric clothing material, involving one each of two monomers, hexamethylene diamine and adipic acid, reacting to form a dimer of Nylon 66.



At this point, the polymer could grow in either direction by bonding to another molecule of hexamethylene diamine or adipic acid, or to another dimer. As the chain grows, the short chain molecules are called oligomers. This reaction process can, theoretically, continue until no further monomers and reactive end groups are available. The process, however, is relatively slow and can take up to several hours or days. Typically this process breeds linear chains that are strung out without any cross-linking or branching, unless a tri-functional monomer is added.

Polymer Chemical Structure

The monomers in a polymer can be arranged in a number of different ways. As indicated above, both addition and condensation polymers can be linear, branched, or cross-linked. Linear polymers are made up of one long continuous chain, without any excess appendages or attachments. Branched polymers have a chain structure that consists of one main chain of molecules with smaller molecular chains branching from it. A branched chain-structure tends to lower the degree of crystallinity and density of a polymer. Cross-linking in polymers occurs when primary valence bonds are formed between separate polymer chain molecules.

Chains with only one type of monomer are known as homopolymers. If two or more different type monomers are involved, the resulting copolymer can have several configurations or arrangements of the monomers along the chain. The four main configurations are depicted below:

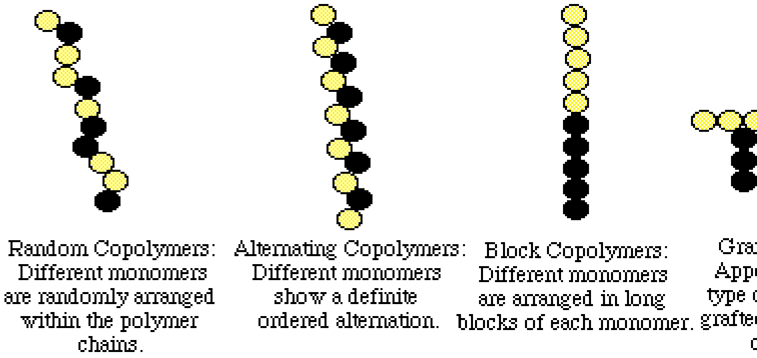


Figure 2: Copolymer configurations.

Polymer Physical Structure

Segments of polymer molecules can exist in two distinct physical structures. They can be found in either crystalline or amorphous forms. Crystalline polymers are only possible if there is a regular chemical structure (e.g., homopolymers or alternating copolymers), and the chains possess a highly ordered arrangement of their segments. Crystallinity in polymers is favored in symmetrical polymer chains, however, it is never 100%. These semi-crystalline polymers possess a rather typical liquefaction pathway, retaining their solid state until they reach their melting point at T_m.

Amorphous polymers do not show order. The molecular segments in amorphous polymers or the amorphous domains of semi-crystalline polymers are randomly arranged and entangled. Amorphous polymers do not have a definable **T_m** due to their randomness. At low temperatures, below their glass transition temperature (T_g), the segments are immobile and the sample is often brittle. As temperatures increase close to **T_g**, the molecular segments can begin to move. Above **T_g**, the mobility is sufficient (if no crystals are present) that the polymer can flow as a highly viscous liquid. The viscosity decreases with increasing temperature and decreasing molecular weight. There can also be an elastic response if the entanglements cannot align at the rate a force is applied (as in silly putty). This material is then described as visco-elastic. In a semi-crystalline polymer, molecular flow is prevented by the portions of the molecules in the crystals until the temperature is above **T_m**. At this point a visco-elastic material forms. These effects can most easily be seen on a specific volume versus temperature graph.

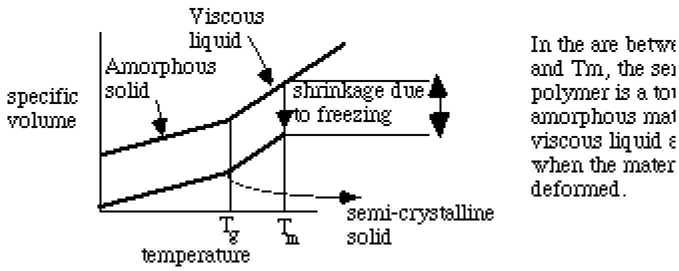


Figure 3: Specific Volume versus Temperature graph.

III. TYPE AND CLASSIFICATIONS

The word *polymer* designates an unspecified number of monomer units. When the number of monomers is very large, the compound is sometimes called a high polymer. Polymers are not restricted to monomers of the same chemical composition or molecular weight and structure. Some natural polymers are composed of one kind of monomer. Most natural and synthetic polymers, however, are made up of two or more different types of monomers; such polymers are known as copolymers.

Organic polymers play a crucial role in living things, providing basic structural materials and participating in vital life processes. For example, the solid parts of all plants are made up of polymers. These include cellulose, lignin, and various resins. Cellulose is a polysaccharide, a polymer that is composed of sugar molecules. Lignin consists of a complicated three-dimensional network of polymers. Wood resins are polymers of a simple hydrocarbon, isoprene. Another familiar isoprene polymer is rubber.

Figure 4 natural rubber

Other important natural polymers include the proteins, which are polymers of amino acids, and the nucleic acids, which are polymers of nucleotides—complex molecules composed of nitrogen-containing bases, sugars, and phosphoric acid. The nucleic acids carry genetic information in the cell. Starches, important sources of food energy derived from plants, are natural polymers composed of glucose.

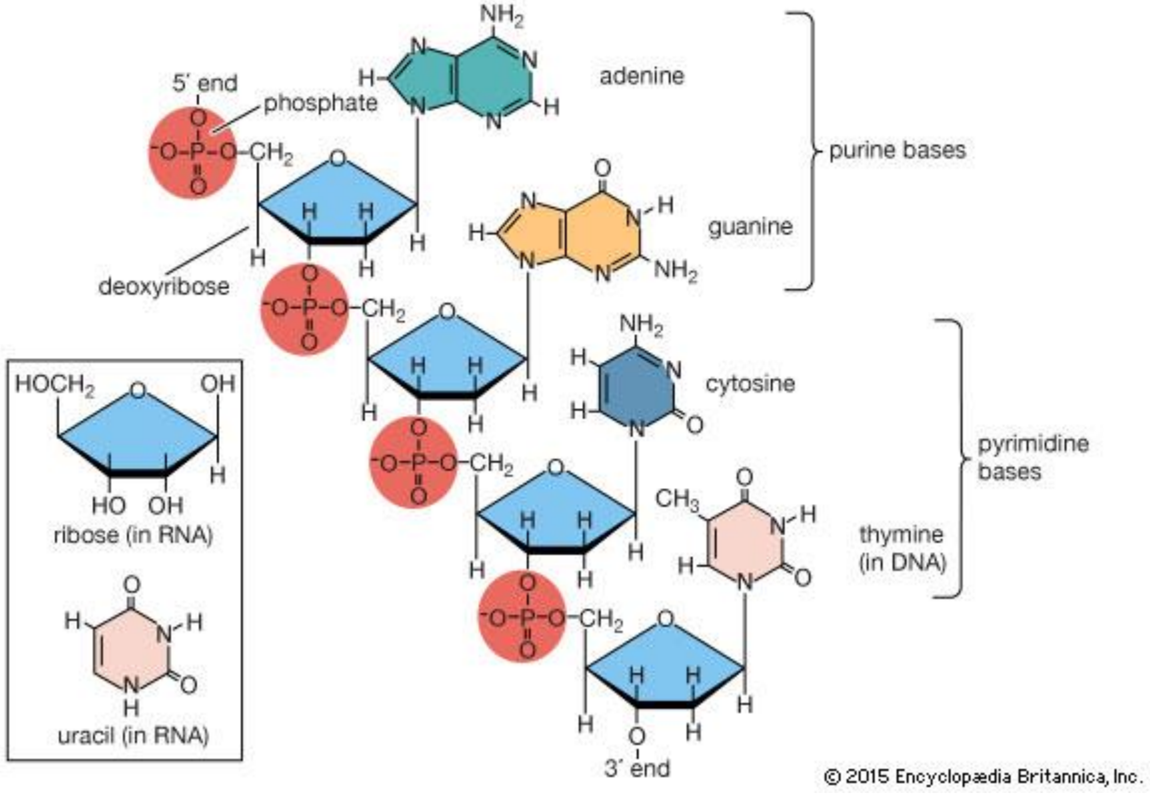


Figure 5 Portion of polynucleotide chain of deoxyribonucleic acid (DNA)

Many inorganic polymers also are found in nature, including diamond and graphite. Both are composed of carbon. In diamond, carbon atoms are linked in a three-dimensional network that gives the material its hardness. In graphite, used as a lubricant and in pencil “leads,” the carbon atoms link in planes that can slide across one another.

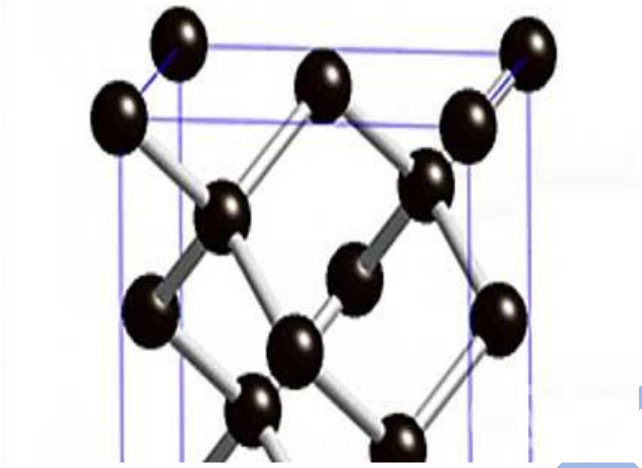


Figure 6 diamond

Synthetic polymers are produced in different types of reactions. Many simple hydrocarbons, such as ethylene and propylene, can be transformed into polymers by adding one monomer after another to the growing chain. Polyethylene, composed of repeating ethylene monomers, is an addition polymer. It may have as many as 10,000 monomers joined in long coiled chains. Polyethylene is crystalline, translucent, and thermoplastic—i.e., it softens when heated. It is used for coatings, packaging, molded parts, and the manufacture of bottles and containers. Polypropylene is also crystalline and thermoplastic but is harder than polyethylene. Its molecules may consist of from 50,000 to 200,000 monomers. This compound is used in the textile industry and to make molded objects.

Other addition polymers include polybutadiene, polyisoprene, and polychloroprene, which are all important in the manufacture of synthetic rubbers. Some polymers, such as polystyrene, are glassy and transparent at room temperature, as well as being thermoplastic. Polystyrene can be coloured any shade and is used in the manufacture of toys and other plastic objects.

Figure 7 polystyrene

If one hydrogen atom in ethylene is replaced by a chlorine atom, vinyl chloride is produced. This polymerizes to polyvinyl chloride (PVC), a colourless, hard, tough, thermoplastic material that can be manufactured in a number of forms, including foams, films, and fibres. Vinyl acetate, produced by the reaction of ethylene and acetic acid, polymerizes to amorphous, soft resins used as coatings and adhesives. It copolymerizes with vinyl chloride to produce a large family of thermoplastic materials.

Figure 8 PVC piping

Many important polymers have oxygen or nitrogen atoms, along with those of carbon, in the backbone chain. Among such macromolecular materials with oxygen atoms are polyacetals. The simplest polyacetal is polyformaldehyde. It has a high melting point and is crystalline and resistant to abrasion and the action of solvents. Acetal resins are more like metal than are any other plastics and are used in the manufacture of machine parts such as gears and bearings.

A linear polymer characterized by a repetition of ester groups along the backbone chain is called a polyester. Open-chain polyesters are colourless, crystalline, thermoplastic materials. Those with high molecular weights (10,000 to 15,000 molecules) are employed in the manufacture of films, molded objects, and fibres such as Dacron.

The polyamides include the naturally occurring proteins casein, found in milk, and zein, found in corn(maize), from which plastics, fibres, adhesives, and coatings are made. Among the synthetic polyamides are the urea-formaldehyde resins, which are thermosetting. They are used to produce molded objects and as adhesives and coatings for textiles and paper. Also important are the polyamide resins known as nylons. They are strong, resistant to heat and abrasion, noncombustible, and nontoxic, and they can be coloured. Their best-known use is as textile fibres, but they have many other applications.

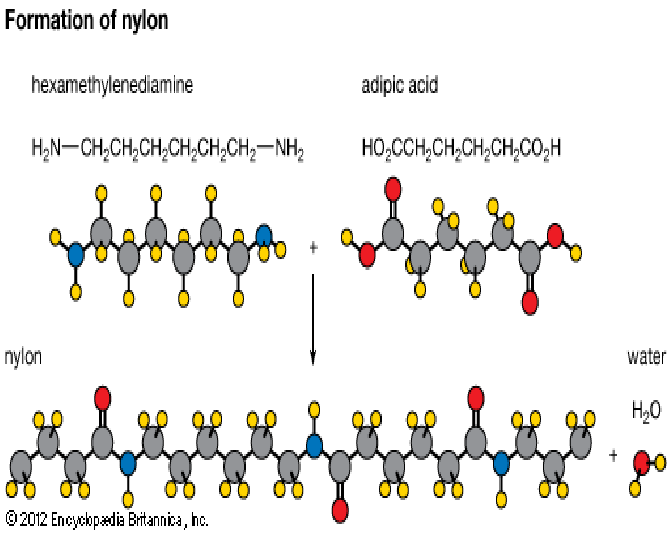


Figure 9 nylon.

Another important family of synthetic organic polymers is formed of linear repetitions of the urethane group. Polyurethanes are employed in making elastomeric fibres known as spandex and in the production of coating bases and soft and rigid foams.

A different class of polymers are the mixed organic-inorganic compounds. The most important representatives of this polymer family are the silicones. Their backbone consists of alternating siliconand oxygen atoms with organic groups attached to each of the silicon atoms. Silicones with low molecular weight are oils and greases. Higher-molecular-weight species are versatile elastic materials that remain soft and rubbery at very low temperatures. They are also relatively stable at high temperatures

Two important developments in the creation of synthetic polymers occurred at the turn of the century. One was the development of Galalith, an ivory-like substance made from formaldehyde and milk, by German chemist Adolf Spitteler. An even more important innovation happened in 1907, when Belgian-American chemist Leo Baekeland (1863-1944) introduced Bakelite. The latter, created in a reaction between phenol and formaldehyde, was a hard, black plastic that proved an excellent insulator. It soon found application in making telephones and household appliances, and by the 1920s, chemists had figured out how to add pigments to Bakelite, thus introducing the public to colored plastics.

IV. POLYMER CHARACTERIZATION

Characterization of polymers is important for when new materials are synthesized, when a competitive product is being evaluated, or when the performance of a product needs to be improved. Polymer Characterization includes determining molecular weight distribution, the molecular structure, the morphology of the polymer, thermal properties, mechanical properties, and any additives. It is a complex and multi-faceted process that should only be done by those with years of experience and strong educational backgrounds--our scientists at PSI are equipped with both.

Approaches

We have multiple approaches for Polymer Characterization. The following is a list of the most common techniques we use.

Polymers inherently have a distribution of chain lengths resulting in a molecular weight distribution. Molecular weight is the size of the molecules that comprise a plastic or rubber material. The properties of the polymer during processing and in the application are influenced by the polymer's molecular weight distribution. For example, lower molecular weight chains help improve melt processing, while the higher molecular weight fraction can be critical to mechanical properties. Additionally, molecular properties vary over the life cycle of a material. The molecular weight value of a polymer will change as the polymer progresses through stages such as raw material, molding, sterilization, and storage. Molecular weight analysis is often determined by one of the following methods:

- Gel Permeation Chromatography (GPC):

Gel Permeation Chromatography (GPC), also known as Size Exclusion Chromatography (SEC), separates polymer molecules based on their size. GPC is used to measure the molecular weight distribution of polymer samples. Absolute molecular weight measurements are performed using multi-angle light scattering (MALS) detection. GPC-MALS molecular weight measurements provide the absolute, or true, molecular weight of a sample without reference to polymer calibration standards. Molecular weight measurements can also be performed using GPC with conventional column calibration, in which molecular weights are calculated relative to a series of polymer standards.

- Dilute Solution Viscosity Testing (IV)

DSV is a very general category of tests, all of which involve dissolving a polymer within a solvent and then measuring flow times in a viscometer. Once the flowtime is measured there are many options for calculations, to include: Relative Viscosity, Reduced Viscosity, Inherent Viscosity, and Intrinsic Viscosity. By measuring the flow time of a polymer solution through a precision capillary, we can measure the viscosity which relates to molecular weight.

- Melt Flow Index Testing (MFI)

Melt flow rate depends on molecular weight, additives, and other ingredients. The melt flow index value allows for direct comparison of materials to each other and is a valuable tool for quality assurance. The sample must be "meltable" in order to be evaluated using the MFI instrument. To charge the instrument with the sample, the sample has to have a particle size that is on the order of about 3-mm or less so that it can be loaded into the barrel portion of the instrument. So, typical plastic pellets are an appropriate particle size. The measurement involves weighing the mass of a plastic that flows from the instrument over a timed interval. Some polymer materials (polyethylene for bag applications) have such high flow rates that the MFI method in that case must be an automated system to obtain reliable results.

Molecular Structure determines if a polymer is a homopolymer or a copolymer, for example. Methods we use for this analysis include:

- Fourier Transform Infrared Spectroscopy (FTIR)

Infrared spectroscopy (IR spectroscopy) is the subset of spectroscopy that deals with the infrared region of the electromagnetic spectrum. It can be used to identify compounds or investigate sample composition.

The infrared spectrum of a sample is collected by passing a beam of infrared light through the sample. Examination of the transmitted light reveals how much energy was absorbed at each wavelength. This can be done by using a Fourier transform instrument to measure all wavelengths at once. From this, a transmittance or absorbance spectrum can be produced, showing at which IR wavelengths the sample absorbs. Analysis of these absorption characteristics reveals details about the molecular structure of the sample. The Infrared Spectrometer provides data over the range from 4000 to 400 cm-1 with the main instrument bench and a somewhat narrower range of analysis (4000 to approximately 650 cm-1) when an attenuated total reflectance accessory is used.

Thin coatings can be evaluated directly on a reflective substrate (reflection-absorbance mode) and powder materials can be evaluated using the diffuse reflectance mode.

- Nuclear Magnetic Resonance Spectroscopy (NMR)

Most nuclear magnetic resonance spectra are obtained on soluble materials or extracts. However, under special circumstances solid materials can also be analyzed. NMR analysis is performed on polymers, copolymers, and additives. The most commonly used elements analyzed for structural determination of organic polymers and small molecules are proton (1H) and carbon (13C). Other elements can be analyzed as well, such as silicon (29Si) and fluorine (19F).

NMR is a complimentary technique to Fourier Transform Infrared Spectroscopy (FTIR).

We will help you to determine which method is right for your testing needs.

Determining the morphology can answer questions such as: Is the sample crystalline? Is the sample phase separated? What size are the domains? We use the folowing analytical methods to determine the morphology:

- Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) magnifies a specific sample region using a high energy focused beam of electrons. The sample is under vacuum to ensure the electron beam stays focused and does not interact with particles in the air. When the beam of electrons hits the sample, it causes secondary electrons to be released from the sample which are detected to provide an image based off the topography of the surface. The two detectors most commonly used include the Secondary Electron Detector (SED) and the Backscattered Electron (BSE) Detector.The electrons interact with the detector to create an image.

This powerful electron microscope is capable of magnifying up to 500,000 times! SEM Analysis is more powerful than Optical Microscopy not only because of the much increased magnification power but also because of the increase in depth of field.

How does EDS Analysis work?

The sample region evaluated with SEM Analysis can also be analyzed to determine the specific elements that comprise the sample region by utilizing Energy Dispersion Spectroscopy (EDS). X-rays are also released from the surface of the sample that carry a unique energy signature that are specific to elements found in the sample. These X-rays are detected with the EDS detector to give elemental information about the sample. EDS provides data about the chemical composition of the sample and provides additional data about the features that are observed in the SEM micrographs. This combined technique is referred to as SEM-EDS or SEM-EDX Analysis.

- Transmission Electron Microscopy (TEM)

A concentrated beam of electrons passes through a very thin sample. Based on electron density the various areas of the sample interact with the beam differently. The resulting image represents the gradient areas of electron density.

Approaches

Transmission Electron Microscopy Analysis is a great approach for documenting the phase distribution of copolymers and blends. Many samples have sufficient contrast in an as-prepared state. However, to obtain sufficient contrast with some specimens, a staining technique is utilized. For example, unsaturated components within a matrix are stained with ruthenium tetroxide. This method will reveal the rubber phase distribution in a polystyrene matrix.

Ultra thin specimens are prepared using a microtome or a cryo microtome on polymer pieces or embedded specimens

- Atomic Force Microscopy (AFM)

The primary uses of Atomic Force Microscopy are to characterize either nano-phase morphology or surface roughness. It is also an excellent tool for the analysis of the phase morphology of microphase separated block copolymer systems or other nanoscale products.

Approaches

Many samples require a customized approach to adapt to the AFM method. Our scientists have the experience and educational background to develop an appropriate approach to ensure reliable results.

V. APPLICATIONS OF POLYMERS:

Agriculture and Agribusiness

- Polymeric materials are used in and on soil to improve aeration, provide mulch, and promote plant growth and health.

Medicine

- Many biomaterials, especially heart valve replacements and blood vessels, are made of polymers like Dacron, Teflon and polyurethane.

Consumer Science

- Plastic containers of all shapes and sizes are light weight and economically less expensive than the more traditional containers. Clothing, floor coverings, garbage disposal bags, and packaging are other polymer applications.

Industry

- Automobile parts, windshields for fighter planes, pipes, tanks, packing materials, insulation, wood substitutes, adhesives, matrix for composites, and elastomers are all polymer applications used in the industrial market.

Sports

- Playground equipment, various balls, golf clubs, swimming pools, and protective helmets are often produced from polymers.

VI. CONCLUSION

Just as nature has used biological polymers as the material of choice, mankind will chose polymeric materials as the choice material. Humans have progressed from the Stone Age, through the Bronze, Iron, and Steel Ages into its current age, the Age of Polymers. An age in which synthetic polymers are and will be the material of choice. Polymeric materials have a vast potential for exciting new applications in the foreseeable future. Polymer uses are being developed in such diverse areas as: conduction and storage of electricity, heat and light, molecular based information storage and processing, molecular composites, unique separation membranes, revolutionary new forms of food processing and packaging, health, housing, and transportation. Indeed, polymers will play an increasingly important role in all aspects of your life.

The large number of current and future applications of polymeric materials has created a great national need for persons specifically trained to carry out research and development in polymer science and engineering. A person choosing a career in this field can expect to achieve both financial reward and personal fulfillment.

VII. REFERENCE:

[1]. Gunton JD, Miguel MS, Sahni PS. In: Domb C, Lebowitz JL, editors. Phase transition and critical phenomena, vol. 8. New York: Academic Press; 1983. p.269.
[2]. Hashimoto T. Structure of polymer blends. In: Cahn RW, Haasen P, Kramer EJ, editors. Structure and properties of polymers. Materials science and technology, vol. 12. Weinheim: VCH; 1993. p. 251.
[3]. Bates FS, Fredrickson GH. Phys Today 1999;52:32.
[4]. Jinnai H, Nishikawa Y, Koga T, Hashimoto T. Macromolecules 1995;28:4782–4.
[5]. Jinnai H, Koga T, Nishikawa Y, Hashimoto T, Hyde ST. Phys Rev Lett 1997; 78:2248–51.
[6]. Jinnai H, Nishikawa Y, Morimoto H, Koga T, Hashimoto T. Langmuir 2000; 16:4380–93.
[7]. Miller MK. Atom-probe tomography: analysis at the atomic level. New York: Kruwer Academic/Plenum Press; 2000.
[8]. Spontak RJ, Williams MC, Agard DA. Polymer 1988;29:387–95.
[9]. Kawase N, Kato M, Nishioka H, Jinnai H. Ultramicroscopy 2007;107:8–15.
[10]. Ito T, Matsuwaki U, Otsuka Y, Katagiri G, Kato M, Matsubara K, et al. In: Vielstich W, Gasteiger HA, Yokokawa H, editors. Handbook of fuel cells, vol. 5. New Jersey: John Wiley & Sons; 2009.
[11]. Bracewell RN. Aust J Phys 1956;9:297.
[12]. Cormack AM. J Appl Phys 1963;34(9):2722.
[13]. Hounsfield GN. A method and apparatus for examination of a body by radiation such as X or gamma radiation. The Patent Office, London, England; 1972.
[14]. Rosier DJd, Klug A. Nature 1968;217:130.
[15]. Hoppe W, Langer R, Knesch G, Poppe C. Naturwissenschaften 1968;55:333.
[16]. Hart RG. Science 1968;159:1464.
[17]. Crowther RA, DeRosier DJ, Klug A. Proc R Soc London 1970;A317:319–40.
[18]. Vainshtein BK. Sov Phys Crystallogr 1970;15(5):781.
[19]. Ramachandran GN, Lakshminarayanan AV. Proc Natl Acad Sci U S A 1971; 68(9):2236.
[20]. Gordon R, Bender R, Herman GT. J Theor Biol 1970;29:471.