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Polymer Science and Technology: A Status Report

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ABSTRACT

Polymers are very important and used in homes, cars, offices, and hospitals–almost everywhere, in fact. Without them, modern life would be very difficult if not impossible. This paper describes the current status of polymer science and technology. Future trends and prospects in polymer materials are also elaborated. The question of alternative raw material resources is addressed. The rapid growth of polymer materials in the past resulted from innovative ideas and the dedication of many chemists and engineers. Current problems are availability and high cost of petroleum raw materials and energy, increased labor costs, increased processing costs, environmental regulations, an overwhelming emphasis on short-range application research with the goal of almost immediate marketability, and cutbacks in fundamental and exploratory research. These trends, unless reversed, do not auger well for continued growth of polymers at anything approaching the 1945-1975 rate.

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INTRODUCTION

Polymer materials are a valuable and integral part of modern life and are examples of useful technology. They are one of the most versatile innovations of chemistry, tailored for hundreds of uses and constantly evolving into even more beneficial products.

Polymers are truly giant molecules whose molecular weight can range from 10,000 to 1,000,000 or even higher. Thus, it is even possible to "see" one of these giant molecules in the form of a vulcanized automobile tire or a molding of phenol/formaldehyde resin with the unaided eye.

The physical properties of polymeric materials can vary markedly (rubbery, rigid, tough, water resistant, water soluble, etc.) depending on the chemical composition and lengths of the chains that make up the molecules. Most of the solid things we see around us (fibers, cloth, rubber adhesives, floor tiles, surface coatings, etc.) are polymers, as is all living tissues. People are polymers, albeit very complex ones. Obviously then, these giant molecules or polymers can and do occupy an important place in our daily lives. Without them life would be very difficult or impossible.

Polymers are made through chemical reactions which link together small molecules, called monomers, to form large molecules with constantly repeating patterns, called polymers. Depending on the monomers, the way the molecules are linked, and the chemical process used in their manufacture, polymers can possess a wide variety of properties. Some are much stronger than steel, others can be made into very light, expandable foams. More than ever, high performance plastics are becoming the materials of choice for use in construction, automotive design, medical applications, and many other important areas.

Polymer science and technology is a relatively young discipline. Today, it offers more than 40 different families of polymers for everything from the nose cones of space vehicles to artificial heart valves to plastic turf for sports. Polymer materials are used in homes, cars, offices and hospitals–almost everywhere, in fact.

One objective of this paper is to describe the current status of polymers. A further objective is to describe future trends and prospects in polymers and plastics, specifically new processes and new materials. The third objective is briefly to summarize some aspects of alternative raw material resources, environmental implications of polymer technology, fundings of research, and overall forecast for polymers and plastics during and beyond the next 10 years.

DEVELOPMENT OF POLYMERS

Historical

Early man used a variety of naturally occurring polymers, e.g., stone, wood, bark, animal skins, cotton, wool, silk, natural rubber, and glass.

During prehistoric time man began to modify the naturally occurring polymeric materials to make them more suitable for his use. These modifications were initially mechanical. More complex mechanical modifications such as twisting cotton, wool, and flax to form threads, and then weaving the threads into cloth came later. Thin-skinned parchment and papyrus vegetable tissue were developed for writing. The mechanical modification of cellulose fibers to make paper was developed by the Arabs in Spain in the 12th century.

Whereas mechanical modifications of natural polymers have been practiced for centuries, the use of chemical modification to make entirely new materials is comparatively recent; certainly almost all of the latter has taken place within the last century. Examples of chemically modified natural polymers include regenerated cellulose, cellulose nitrate, and cellulose acetate. The greatest progress occurred, however, when mankind started using the raw chemical building blocks found in nature, namely, coal and petroleum, to make synthetics. It then became possible to design new products for specific uses by molecular tailoring and engineering.

Chemistry

Polymer chemistry began in 1920 when Staudinger introduced the concept of large covalently bonded macromolecules. It was Mark who introduced the concept of chain branching. The brilliant synthetic chemist Carothers synthesized polyesters and polyamides and introduced the concept of the distribution of molecular weight in a single chemical species. Copolymerization was advanced by Price and Alfrey and Ham. By 1950 polymer chemistry was a well-established and worthwhile discipline.

The synthesis, characterization, processing, and applications of polymers are described in a very large number of articles and books. Readers may wish to refer to some important books in this area [1-6].

Important chemical and other modifications of polymers are as follows:

Copolymerization

Cross-linking of rubbers and plastics. Cross-linking methods: sulfur, peroxides (and other free radical formers), radiation (UV, E-beam, gamma), and moisture

Grafting. Chemical reactions on side chains or chain ends (hydrolysis, esterification, etherification, and polyelectrolyte formation)

Interpenetrating polymer networks

Polyblending

Plasticizing

Filling and reinforcing (carbon black, particulate fillers, fiber reinforcement)

Orientation, uniaxial (fibers) and biaxial (films)

Annealing

Technology

Current State. At the present time monomer building blocks are converted into polymers from which finished products are made. This is a very mature technology with very large scale production. The processing of thermoplastics, thermosets, and rubbers is well developed. A wide range of low cost polymers is available, with properties to satisfy most end-use requirements. Specialty polymers are also available at higher costs for high performance applications (high temperature, high impact, cryogenic, fire retardant). Chemical and other methods of polymer modifications are extensively used. In recent years polymers for medical applications (artificial kidneys, etc.) and optical applications, including optical fibers, have been developed. Radiation processing, composite technology, and development of finished products directly from monomers in a single step are rapidly growing fields. We shall discuss them in the next section.

Fields of Polymer Applications. The fields of polymer applications are listed below:

a. Textile fibers–Cellulosic, nylon, polyester, acrylic, polypropylene
b. Monofilaments and bristles–Nylon, polyester
c. Surface coatings–Polyvinyl acetate and acrylic latices; alkyds, linseed, and other drying oils; acrylic, polyester powder
d. Films–Polyethylene, polypropylene, cellulosic, terephthalate esters, polystyrene
e. Sheets–Polyethylene, polypropylene, cellulose acetate, polymethyl methacrylate
f. Adhesives and glues–Epoxies, polyesters, rubber latices, rubber-solvent cements, cyanoacrylates

g. Composites–Epoxies, polyesters, polyurethane, phenolics
h. Rubbers and elastomers–Natural rubber, copolystyrene/butadiene, copolyethylene/propylene, butyl, copolybutadiene/acrylonitrile, neoprene, fluorinated ethylene/propylene, silicones, copolyethylene/vinyl acetate, plasticized polyvinyl chloride
i. Injection molding–Polystyrene, acrylonitrile-butadiene-styrene (ABS), polyethylene, polypropylene, nylon, polyesters, polycarbonate, polymethyl methacrylate
j. Compression molding–Phenolic, epoxy, diallyl phthalate (DAP), silicones, rubbers
k. Extrusion–Polystyrene, ABS, polyethylene, polypropylene, nylon, polyesters, polycarbonate, polymethyl methacrylate, PVC, rubbers
l. Vacuum forming–Polystyrene, ABS, polyethylene, polypropylene, nylon, PVC (rigid)
m. Calendering–PVC, rubbers
n. Structural materials for housing and other uses–Epoxy/glass composites, reaction injection molding (RIM), corrugated PVC, polyester/glass corrugated composites, epoxy/graphite fiber composite
o. Plumbing–PVC, polyethylene, polyester/glass, epoxy/glass
p. Floor coverings–PVC, asphalt, rubbers
q. Automotive–ABS, PVC, rubbers, RIM
r. Thermal and acoustic insulation–Polystyrene (bead foams and styrofoam), polyurethane, polyisocyanurates, urea/formaldehyde, phenolic, "instant" foam
s. Flotation–Polystyrene, polyurethane
t. Packaging–Polystyrene, PVC, cellulosic, ABS, polyethylene, polypropylene, polyesters
u. Electrical and electronic–PVC, polyethylene, polypropylene, x-linked polyethylene, rubbers
v. Ion exchange, flocculation–Polyelectrolytes, oil well drilling muds
w. Biomedical–Silicones, polyurethane, polyacrylonitrile, cellulose acetate
x. Encapsulation–Gelatin, polyvinyl alcohol, polyelectrolytes
y. Space applications–Polyurethane solid rocket fuels, polyimide textiles, phenolic ablative

End-Use Products of Polymers. The end-use products of polymers are listed below:

a. Textile–Clothing, carpets, blankets, recreational surfaces, curtains, draperies
b. Monofilaments–Fishing line, brushes, weed eaters, optical fibers, seat covers, twine, rope
c. Surface coatings–Enamels, lacquers, latex paint, powder coatings (fluidized bed, electrostatic)
d. Films–Photographic film, rain coats, shower curtains, upholstery, luggage

e. Sheets–Window panes, partitions, floor tile, table and counter tops, vacuum formed products
f. Adhesives and glues–Household glues, caulking materials, sealants, joining and fastening (autos, planes, boats, appliances)
g. Composite–Plywood, particle board, laminates, filament fiber reinforced composites (boats, autos, planes), filament wound composites (tanks, pressure vessels), safety glass
h. Rubber and elastomers–Tires, rubber hoses, rubber gaskets, footwear, rainwear, floor tile
i. Injection molding–Toys, nylon gears, automotive parts, wall tile, brush handles, appliances (TV cabinets, etc.), golf tees
j. Compression molding–Electrical and electronic components, silicone rubber molds, O-rings, gasket seals
k. Extrusion–Pipe, tubes, rods, special shapes, house siding, packaging film, garbage bags, Astroturf, diaper liners.
l. Vacuum forming–Meat trays, egg trays, containers, appliance housings, refrigerator liners
m. Calendering–Upholstery, wall covering, luggage, rainwear, rubber sheeting
n. Structural–Doors for houses, window frames, corrugated roofing, solar collectors, auto fenders and hoods
o. Plumbing–Water pipe, sewer pipe, shower stalls, sinks, tubs
p. Floor coverings–Floor tiles, lineoleum, paints
q. Automotive–Front fascia, fenders, hoods, dashboards, steering wheels, cushions, and seats
r. Thermal and acoustic insulation–House insulation, auto insulation, cushions, acoustic tile, partitions
s. Floatation–Life preservers, water skis, buoys, boats, balloons
t. Packaging–Meat trays, egg crates, shipping containers, beverage containers, food packaging, milk containers, medicinal packaging
u. Electrical and electronic–PE and PVC coated wires and cables, optical fibers, electronic components (printed circuits, display devices, discretes), telephone switches
v. Ion exchange, flocculation–Water softening, soil conditioners, oil well drilling muds, sugar cane clarification, ion exchange columns, battery separators
w. Biomedical–Artificial heart, heart valves, artificial arteries, heart pace makers, blood oxygenators, artificial kidneys, blood bags
x. Encapsulation–Encapsulated medicines ("Contact"), carbonless paper, fungicides, pesticide
y. Space applications–Solar collectors, solid rocket propellant, reentry heat shields, flexible self-rigidizable structures (antennas, shelters), solar sails

PROSPECTS FOR POLYMER MATERIALS DURING THE NEXT TEN YEARS

Growth Trends in Existing Polymers

Polymers made from the simplest hydrocarbon precursors (such as ethylene, propylene, other olefins) will continue to grow in total usage at a higher rate than other more complex and higher cost polymers (such as ABS, nylon, etc.). Growth of ethylene and propylene polymers will be supported by intensive research to improve the physical properties, performance characteristics, and processing of these lowest cost polymers via filling, polyblending, grafting, cross-linking, etc.

The Middle East, specifically Saudi Arabia, will become a bigger factor in world markets as new linear low-density, low-density, and high-density polyethylene plants come on stream at Al-Jubail and Yanbu around 1984 [7]. American, but mostly European producers, are laboring under problem of excess capacities and low demand and as such must resort to intensive research to improve low cost polyethylenes.

Although ultrahigh molecular weight polyethylene (UHMW-PE) has outstanding toughness and chemical inertness, its thermoformability is poor, and therefore moderate growth is foreseen in its use. Because of exceedingly high melt viscosities, UHMW-PE is generally fabricated by positive displacement methods; e.g., compression molding or ram extrusion. A UHMW-PE having a molecular weight in the range of 2-5 millions is extremely difficult to reinforce with fillers, but techniques to fill UHMW-PE will be developed. It is also likely that most of the benefits of ultrahigh molecular weight can be obtained more economically by radiation cross-linking (e.g., electron beam bombardment).

Fiber-reinforced and other composite materials will accelerate their present growth rate as a route to both improved performance and/or lower cost. For the same reasons the usage of graphite fibers for reinforcement in composites will expand. The quantum jump in use of the graphite fiber will come when graphite-reinforced composites start replacing steel in the auto industry. This could well happen to a significant extent by 1990. At any rate, some of the graphite fiber producers are banking on it. Extensions of existing polymer supplies via use of low-cost fillers will expand rapidly in the 1980-1990 time period. This current "art" will become a highly developed science with preferred filler types and concentrations defined for each application. More importantly, research will be done to find low cost ways to process highly filled materials.

In the future, plastics, e.g., phenolics, ABS, and SAN, will be utilized in new composite building materials. The work of Usmani and Salyer represents a substantial technological breakthrough in upgrading of the polymeric properties of bagasse and other agricultural residues, and merits further development leading to commercialization [8-10].

Because of limited global petroleum reserves, we anticipate there will be a much stronger emphasis on recycling of all polymeric materials and most of the present throwaway applications will be modified or discontinued.

New Advances in Polymers

The development of entirely new polymer compositions will be minimal during the next 10 years and even beyond.

New advances in polymer materials will be in the following areas which we shall discuss.

a. Development of high-strength high-temperature, i.e., high-performance plastics
b. Electrical conductors or semiconductors
c. Pyroelectric polymers (generate electricity on temperature change) and piezoelectric polymers (generate electricity on deformation)
d. Specialty polymers for specific applications
e. Specialty polymers with specific performance characteristics
f. High-performance thermoset polymers

High-Performance Engineering Plastics.

New models and modifications of "engineering plastics" (that can command a premium price) with improved outdoor durability will continue to emerge from the laboratory into the market place. New varieties of heat and fire-resistant materials will become commercially available and these will likely be based on highly aromatic, condensed-ring polymers similar to the present polyimides, fluorenone polyesters, phenolphthalein polyesters, etc. However, the new models of engineering plastics will provide only incremental or marginal gains in properties rather than breakthroughs to new performance plateaus.

Polyester carbonates will be developed to replace an older generation of heat- and impact-resistant polymers, namely, polycarbonates which become brittle in the 80-120°C range. Polyester carbonates are copolymers of bisphenol A, phosgene, and terephthalic acid, and they retain their impact resistance at elevated temperatures, making them ideal for aircraft windows, solar flat-plate collectors, and lenses for street lamps.

Physical mixtures of existing materials to find the properties needed, particularly in polymer blends or "alloys," will grow because the cost of inventing new polymers and monomers is economically not cost-effective.

The blending of polymers is not a new science but tailoring of products through alloying for specific end-use applications is a relatively recent development. One such material that may become commercially important is acrylic modified styrene maleic anhydride that maintains a high level of toughness while maintaining processability and heat resistance. Novel blends based on polypropylene will also soon materialize. Rubber toughened nylon to produce a very rubbery material that is stronger and tougher than the parent materials will also emerge during the next few years.

Electrical Conductors or Semiconductors. Doped stretched-oriented polyacetylenes have conductivities as high as 2000 ohms^{-1} cm^{-1}. The conductivity of copper is 6×10^6 ohm^{-1} cm^{-1}. Thus, eventually, current-carrying polymers could be used in batteries, heating elements for wall coverings, floors, blankets and clothing, and lightweight aircraft wiring. Other doped resins under current development are polyphenylene sulfide and poly(p-phenylene). An all plastic lightweight thin-film battery is a very distinct possibility in the near future.

Among the most frequently mentioned applications for semiconducting polymers are advanced solar cells and semiconducting devices.

Pyroelectric and Piezoelectric Polymers. Polyvinylidene fluoride (PVDF) is the most powerful pyroelectric and piezoelectric polymer. PVDF has been used in microphones, earphones, loudspeakers, burglar alarms, and fire detection devices. PVDF has insufficient sensitivity for infrared television cameras and cannot be used in high-temperature equipment because of rapid aging at 130°C. Nylon 11 is another resin of this class. Its piezoelectricity is about one-half that of PVDF but comparable in pyroelectricity. Other odd nylons, e.g., nylons 3, 5, and 7, should be investigated.

Another area that may see research and development activity is rendering resins piezo- or pyroelectric by poling wherein films are subjected to electrostatic fields of 5000 kV/cm. Poling orients dipoles in the same direction. Resins subjected to poling techniques may be used in infrared television cameras and underwater submarine detection devices.

Specialty Polymers for Specific Applications. "Specialty" polymers, tailored for new and specific applications, are almost certain to grow in the future. Examples of this type include optical fibers, solar glazing, electronic components, electrets, and phase change polymers for thermal energy storage [11-16].

Specialty Polymers with Specific Performance Characteristics. A separate growth area includes specialty polymers wherein a minor amount of an active or functional component is chemically attached to a polymer chain to enhance a specific performance characteristic. Thus the modifying additive cannot be evaporated or leached from the base material. Examples of this type of specialty polymer, which may become commercial products, include the following: Pesticide carriers–localization and control of potentially hazardous compounds, controlled release rate; Drug carriers–transport to specific sites, slow release; Antioxidants and UV screening agents–longer outdoor durability [17, 18]; Polyelectrolytes–separators and solid electrolytes for batteries; Blood compatibilitizing groups–improved artificial organs; Sugar bondings–nonfattening sweetener; and Food color bondings [19-24].

High Performance Thermoset Polymers. Acetylene terminated monomers and resins are a potentially attractive approach to high-strength, high-temperature polymer materials for moldings, coatings, adhesives, sealants, and composites. One example is a resin made by reacting 1 mol of 1,3-bis-(3-aminophenoxy)benzene with 2 mol of 3,3',4,4'-benzophenonetetracarboxylic dianhydride to form a diimide dianhydride followed by capping with 3-ethynylaniline to give acetylene-terminated tetraimide.

Over the past several years, Arnold and co-workers have synthesized a family of new polymers derived from acetylene-terminated monomers [25, 26]. These resins are known to exhibit high thermal stability, good adhesion characteristics, and high moisture resistance. We anticipate that these resins may find use as graphite fiber composite binders and as aircraft metal adhesive binders. Usmani has recently suggested that acetylene-terminated sulfones and acetylene-terminated resins be utilized as electronics plastics [27]. Acetylene-terminated monomers and resins made by Arnold and co-workers are slightly brittle and hence need internal or external modification.

Exploratory Polymer Developments

Yajima and co-workers have prepared silicon carbide polymers from carbosilane [28-30]. They spun the polycarbosilane into fibers and heat treated them to make silicon carbide fibers. These fibers have high strength and high modulus in high-temperature atmospheres (1200°C) and superiority in heat resistance and oxidation resistance. Silicon carbide fiber reinforced glass-matrix composites have excellent strength at high temperature [31]. Salyer and Chu have recently suggested that polysilastyrene be utilized to make silicon carbide [32]. Polysilastyrene has excellent processability before conversion into silicon carbide; it is soluble in common organic solvents, has a low melting point, and can be molded, drawn into fiber, or cast into films much like conventional organic polymers. In converting it to the silicon carbide, the original form can possibly be retained [32]. Thus products of complicated shapes could be obtained with polysilastyrene. We expect silicon carbide technology to grow during the coming decades.

New Processing Techniques

Some of the most exciting developments in the polymer industry during the next 10 years are expected to involve new processing methods that can lower costs and make new, large, contour area applications practical. Currently, much of the plastic processing is performed by extrusion and injection molding at high temperatures (e.g., 500°F) and very high pressures (e.g., 20,000 psi). These processing conditions are required because high molecular weights are necessary in the preformed polymers to obtain satisfactory mechanical properties. Extrusion and injection molding involve high capital cost and place practical limits on the size (projected area) of the finished parts that can be produced.

A new process that has emerged into significant commercial utilization is "reaction injection molding" (RIM) wherein articles are molded directly from low molecular weight monomeric precursors at low temperature and low pressure. RIM is now being used to make automobile fascia and house window frames and doors. At present, RIM processing is limited almost entirely to urethanes, but other rapidly polymerizing thermosetting resins (epoxies, polyesters, interpenetrating polymer networks, phenolics, acetylene-terminated resins, and diallyl phthalate) are now in development. Heat resistant nylon block copolymers would be particularly useful for automotive and machinery parts that are exposed to high temperatures. It is possible that nylon block copolymers might give very stiff competition to polyurethanes in RIM. Nylon block copolymers are formed by adding caprolactam, polyols, and a catalyst to the mold and have the advantage that they do not stick to the molds.

RIM as well as reinforced RIM (RRIM) processing will undoubtedly greatly expand during the next 10 years.

Other methods of proceeding directly from low molecular weight precursors to finished products are also being actively investigated and probably will also find large scale use. One example is sheet molding compounds (SMC) in which particulate filled resin precursors along with some short fibers are placed in a mold and cured at elevated temperature. SMC, now in large use, permits better fiber reinforcement than is possible with RIM. Capital equipment costs for SMC may also be significantly lower than RIM.

Conventional transfer molding and injection molding of filled phenolic and diallyl phthalate and other thermosetting prepolymers will also increase during the next 10 years, especially for the electronic industry.

A relatively new but moderately growing processing technology involves the use of radiation sources (electron beam and cobalt-60) for both polymerization and after-treatment of polymers. At present the large uses for radiation are: cross-linking of polyethylene wire coatings, polyethylene films, and tubings; and sterilization of medical wares. Other uses of electron beam and cobalt-60 irradiation are mainly confined to polymer after-treatment such as vulcanization of rubbers, graft polymerization, cross-linking of thermoplastics (to make moldings that are "form stable" at elevated temperatures), and insolubilizing of water sensitive polymers (e.g., polyvinyl alcohol textile fibers). Electron beam irradiation is preferred for the thinner cross-section moldings (where the depth of penetration achievable is adequate). Cobalt-60 sources are being increasingly used in thicker cross-section products. Radiation sterilization of hospital supplies is also growing. Almost certainly irradiation processing of polymers and plastics will continue to grow to become a major industry by the turn of the century.

Coatings Developments

Coatings technology is a good example of applied polymer science. Coatings are used for protective as well as decorative function. A history of coating science and technology has been recently provided by Myers [33].

The chemistry and technology of coatings have kept pace with most of the requirements of users. Newer coatings are developed to remove certain deficiencies in current coating systems. Much research was done in the last decade on coatings for safe environment, and it is hoped that new coating systems will materialize during the current decade. High solids coatings will grow in usage because of energy and environmental considerations. Powder coatings will also grow for the same reasons. Water-borne coatings will show limited growth because of inherent problems with aqueous coatings. High bond integrity primers will be developed to achieve full realization of durable adhesive bonded joints. Also, development of improved novel nontoxic multicomponent corrosion inhibitors, specifically for aircraft and ship primers, will emerge in the next few years. Chromates are toxic and hence they will be replaced by inhibitor formulations based on either microencapsulation or adsorption technology.

The traditional applications of coatings—decoration and protection—will continue to occupy paint chemists who will attempt to make them more attractive, longer lasting, less expensive, and easier to use. However, the nontraditional uses will present exciting research challenges, e.g., making a paint to convert solar energy into electricity, solid state electronics to produce power-producing electrical pathways, and polymer coatings to keep and operate personal generating plant in place on a dwelling.

Current coating test methods provide very limited information on the physical and chemical changes in the coating systems during weathering that lead to coating failure. The characterization of weathered coating systems is critical in evaluating long-term performance of coatings and as such it will become necessary to develop physicochemical characterization methods that relate to changes in performance during exposure. Such property change/weathering data can be used effectively to improve the performance life of the coatings. The science of predicting weatherability lags far behind the need. Prediction of the useful lifetime of coatings based on property change/outdoor exposure will be extremely beneficial in the development of future finishes, and it is hoped that such work will be completed in the near future.

Adhesive Developments

Adhesives are the most social of polymer products. Their purpose is to bring different materials together. They function by cooling molten thermoplastic, by solvent evaporation from a latex or resin solution, or by cross-linking (or irreversible) setting. Commonly used resins are formaldehyde resins, starch, dextrin, elastomers, thermoplastic resins, and thermosetting resins.

Anaerobic adhesive compositions are blends of dimethylacrylates or diacrylates with hydroperoxides and other ingredients. These compositions are stable in the presence of air but polymerize when oxygen is excluded. These adhesives were originally developed by General Electric Co. [34], but they were commercially made available by Loctite Corp. [35]. Anaerobic adhesives sell for about $30/lb and are used in locking of nuts and bolts in the automobile industry.

Cyanoacrylates polymerize very rapidly by the moisture of the air and therefore are used in mechanical and electronic assembly and repair as well as in home repairs [36]. Cyanoacrylates sell for about $60/lb.

A coupling agent is a hybrid molecule; two distinct parts have distinct affinities with different materials. Silanes and titanates are useful examples. Coupling agents are among the adhesive materials pointing the way to the future. Heterofunctional adhesives will be developed and grow in usage during this decade.

Presently, and in the future, the development of adhesives will emphasize energy, environment, economics, and excellence. Organic solvent-based adhesives will decline in popularity while water-based acrylic and neoprene formulations will replace flammable solvent cements. The solvent-free adhesives will be favored in their several varieties.

High strength hot melts, based on polyamides and polyesters, may become automobile body solders, along with epoxy systems. Hot melt pressure-sensitives based on acrylics, cross-linkable grade, will be designed to provide heat resistance needed for automobile masking tape that will survive the paint cycle.

For structural adhesives, epoxies are still the favored thermosetting materials either alone or toughened with nylon or nitrile rubber. The most serious problems of epoxies are loss of mechanical properties after exposure to elevated temperature high humidity environments and moisture sensitivity during layup of bonded parts. Flexibilized diallyl phthalate and diallyl phthalate/polyepoxy interpenetrating polymer network structural adhesives have been recently explored by Usmani [37].

Polymeric Foams

Foams are colloidal systems containing a gas as the dispersed phase. The continuous phase may be liquid or solid. Foams have very large interfacial areas and consist of a porous structure having more or less regular unit cells, either open or closed, which are usually formed by generating a gas in a polymerizing resin matrix. Voids are generated in foams by various methods, e.g., air entrainment, depressurization of dissolved gases, vaporization of water of reaction, production of carbon dioxide from chemical reactions, production of nitrogen from decomposition of azo compounds, formation of spherical interstices due to removal of soluble spherical fillers by leaching, filler removal, and solvent evaporation and matrix shrinkage.

Plastic foams, e.g., flexible polyurethane, rigid polyurethane, sponge rubber and latex, polyolefin, polyvinyl chloride, silicone, polystyrene and related thermoplastic, phenolic, urea/formaldehyde, epoxy, polyisocyanurate, polybenzimidazole, polyimide, polyvinyl carbazole, pyranyl, polyester, cellulose acetate, acrylic, fluorocarbon, polysulfone, and ionomer have been discussed by Frisch and Saunders [38]. They have been also treated by Benning [39]. Plastic foam technology is quite established and very mature, and not too much new development will take place in the future.

Man-Made Fibers

The synthetic fiber industry is only about 50 years, yet the annual production is in billions of kilograms. The development of fibers resulted from advances in polymer synthesis and new spinning methods. At the present time nylons, polyesters, acrylics, and polyolefins are the major classes of synthetic fibers. Specialty fibers include Spandex elastic fibers, heat- and flame-resistant fibers from fluoropolymers, polybenzimidazole, aramids, and high-strength, high modulus fibers from graphite and aramids. Fibers have also been made from polymers, e.g., polyvinylidene chloride, polyvinyl alcohol, and homologs of 6-nylons, but they have received no attention. Recently Usmani has made fibers from fluorenone polyesters which have good potential and should be further developed [40].

The fiber business has been very unpredictable in the past. At the present time there is overcapacity but an increase in the use of fibers in carpets and industrial applications is foreseen in countries that are trying to industrialize and improve their standard of living.

Fiber scientists in the future will develop a truly satisfactory flameproof fiber without detracting properties, a low-cost fiber with cottonlike comfort and the durability of nylons or polyesters, an easily-cared for fabric to replace wool, and a family of electroactive fibers with good handling and durability properties.

Elastomers and Rubber Products

The rubber tree, Hevea Brasiliensis, is the primary production unit of the natural rubber industry. Dynamic production and agronomic programs, specially in Malaysia and the Philippines, will help meet the projected demands for rubber products in the future. Prospects for the natural rubber industry are bright because it is a cheap source of rubber products in this age of depleting nonrenewable resources and awareness of environmental pollution.

Synthetic rubber was one of the earlier polymer to be synthesized. During World War II, a giant industry based on styrene-butadiene rubber was established. This is a mature industry and no growth is foreseen.

POLYMER'S ENVIRONMENTAL CONSIDERATION

In general, polymer processing plants are quite safe for the workers. Stricter control requirements in the future could also minimize the impact of polymer processing on the environment.

Because of large compositional and handling variations in plastic processing, there is a pressing need to determine the kinds and quantities of chemical agents to which personnel in the workplace are exposed. We also think that determination of the type, quantity, and source of emissions released under comprehensive and well-defined processing conditions encountered in practice could be useful. A technical approach for this type of work has been proposed by Usmani [41, 42].

FUTURE ALTERNATIVE FEEDSTOCKS FOR POLYMERS

Presently, all polymer materials save cellulosics are made from petrochemicals derived from petroleum or natural gas. Although technologies for the production of chemical and plastics feedstocks from abundant raw materials such as coal, shale, and biomass exist, we speculate the chemical industry in the United States and abroad will not commercialize these technologies now or by 1990. The principal reason is that there is no economic advantage to switch to alternative raw materials at this time. The full line of polymers and plastics will therefore continue to be made from petrochemicals for the next 10 years or so.

However, it is distinctly possible that in the late 1990s, or soon thereafter, in the United States and other industrialized countries, abundant supplies of relatively inexpensive electrical energy may become available from nuclear reactors (breeder and fusion) and/or other nonpetroleum sources. In this case, we could well see large-scale application of some of this electricity for the production of monomers and other hydrocarbons via the calcium carbide-to-acetylene route. From acetylene, ethylene and many other organic compounds can be prepared by established chemical methods.

Whether this nonpetroleum route to an electrical economy is, in fact, implemented will also depend on the emphasis given in the interim to development of energy from coal and shale oil; and the finding of economic solutions to the very large technical and environmental problems associated with large-scale production and use of these fossil fuels.

Almost certainly global politics will likely have a very large and determining influence on which of these alternative futures will materialize.

CONCLUSIONS

The rapid growth of polymers and plastics in the past resulted from the innovative ideas and dedication of many chemists and engineers.

We currently face intermittent and long-term shortages of essential petroleum raw materials and energy (although not as of this writing). Events in the last decade have indicated that oil is no longer cheap and plentiful. Higher energy and labor rates have increased plastic processing costs as well as the conversion costs of these resins into finished consumer and industrial plastic goods. Environmental regulations have further increased plant construction and operation costs and thereby, in effect, decreased productivity.

In addition, we are now confronted with an overwhelming emphasis on short-range application research with the goal of almost immediate marketability. This has been accompanied by major cutbacks in fundamental and exploratory research by most of the major global polymer and plastic manufacturing companies. Thus, there are both a lack of research money and a shortage (or underutilization) of creative polymer researchers for generating new technology. These trends, unless reversed, do not auger well for continued growth of new polymer and plastics technology at anything approaching the 1945-1975 rate.

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