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Introductory Chapter: The Way to Fulfill Science Fiction

Xufeng Dong

1. Introduction

The history of human civilization is accompanied by the progress of materials. Several hundred thousand years ago, our ancestors went out of Africa, and they began to use stones to make weapons to fight with wild animals or build residence. Several thousand years ago, the early civilized human have mastered the skill to make pottery wares. About 3000 BC, the inhabitant of the Crete Island has entered the Bronze Ware Period. Then there was the Iron Age, and while work efficiency has been greatly improved, battles between different countries became more brutal. Since Bessemer Sir Hery invent the converter steelmaking technology in 1856, the industrial revolution entered the Steel Age, which cause the dramatic progress of civilization. We have used steel to make big machines, cars, airplanes, huge ships, skyscrapers, long-span bridges, rocket ships, and so on. During the past 100 years, we have synthesized a large number of polymer materials, which provided us with various tools, wares, clothes, etc. with good properties but low weight and low cost. Recently, smart soft materials that could response to an external stimulus (such as electric field, magnetic field, sound, light, temperature, pH, and so on) as well as functional soft materials that are electronic conductive, magnetic conductive or thermal conductive have attracted considerable attention. They have application potentials in various fields, including artificial muscles, soft wearable materials, sensors, actuators, soft batteries, soft screens, etc. To some extent, they are the way to fulfill most of the “black technology” that described in some science fictions. Following two sections will give a brief introduction on several main smart soft materials and functional soft materials.

2. Smart soft materials

2.1 Shape memory polymers

Shape-memory polymers (SMPs) are those polymers that have the ability to “memorize” a macroscopic (permanent) shape, be manipulated and “fixed” to a temporary and dormant shape under specific conditions of temperature and stress, and then later relax to the original, stress-free condition under thermal, electrical, or environmental command. This relaxation is associated with elastic deformation stored during prior manipulation [1]. Shape-memory polymers have aroused great attention from scientists and engineers due to their capacity to remember two shapes at different conditions. Potential applications for SMPs exist in almost every area of daily life, such as self-repairing auto bodies, kitchen utensils, switches, sensor, intelligent packing and tools, and so on [2]. Other potential applications are drug delivery [3], biosensors, biomedical devices, microsystem components, and

smart textile [4]. Since polymer can be made biodegradable, they can be used as short-term implants where removal by surgery can be avoided.

2.2 Dielectric elastomers

Dielectric elastomers (DEs) are an electronically actuated polymer material. They are the typical investigated electro-active polymers (EAPs) and consist of a low stiffness elastomer placed between two conductive electrodes [5]. The shape or volume of DEs can be changed by external electrical stimulation and can be restored to their original shape or volume when the electrical stimulation is withdrawn. DEs have the characteristics of large actuation strain, high bandwidth, high energy density and high conversion efficiency, good environmental adaptability, long fatigue life, and excellent bionic performance. A feature of DEs is that they can not only convert electrical into mechanical energy actuators (DEAs) but also transduce mechanical into electrical energy generators (DEGs) [6]. In the future, DEs are to be used reliably in applications that include soft robotics, medical devices, artificial muscles, and electronic skins [7].

2.3 Electrorheological composites

Electrorheological (ER) composites have been considered as one kind of intelligent materials, and their rheological properties can be instantaneously and reversibly changed by the applied electric field [8]. As one pioneering example of ER composites, electrorheological fluids (ERFs) are commonly composed of polarizable particles and nonconducting liquid. Their rheological properties including viscosity, shear stress, and yield stress can be switched reversible when an electric field is applied [9]. Due to the special properties, ER fluids can be applied in various fields, such as clutches, brakes, accurate polishing, tactile displays, and sensors. As another kind of ER composites, electrorheological elastomers (EREs) also usually filled with dielectric particle as the dispersion phase, which is quite similar to ERFs. However, rubbers or gels are adopted as the matrix in EREs, which enables them to overcome the defects of particle aggregation and sedimentation of ERF [10]. Under the external electric field, EREs can present a reversible change in storage modulus, loss modulus, and loss factors. Owing to these unique advantages of EREs, they are thought of as promising materials for building base isolation, vibration reduction, noise control in mechanical equipment and electro-active actuators [11].

2.4 Magnetorheological composites

Magnetorheological (MR) composites are a kind of smart soft materials whose rheological properties can be actively changed by applying magnetic fields [12]. Magnetorheological fluids (MRFs) and magnetorheological elastomers (MREs) are two main kinds of magnetorheological composites. Magnetorheological fluids are composed by dispersing magnetizable particles in non-magnetizable fluids. Their rheological parameters such as viscosity and yield stress strongly depend on magnetic field [13]. They can be used to fabricate smart dampers, clutches, actuators, human muscle simulators in various fields. The main difference between the magnetorheological elastomers and the magnetorheological fluids is the fluids-matrix that is replaced by polymer-matrix, in most case is elastomers. Compared with MR fluids, MR elastomers present magnetic field dependent dynamic viscoelasticity, including storage modulus, loss modulus, and loss factors [14]. Such unique properties make them to be employed in a wide range of engineering applications such as suspension bushings, seismic protection, engine mounts, adaptively tuned vibration absorbers, and stiffness tunable isolators [15].

2.5 Field responsive gels

Field responsive gels (smart hydrogels) are smart gels which are capable of responding to external stimuli by changing their physic-chemical properties, such as volume, water content, permeability, and hydrophobicity [16]. Field responsive gels take advantages of the hydrophilic and the high swelling ratio of conventional hydrogels and the environmental responsive properties of functional groups or nanoparticles. With an array of triggering mechanisms, including pH, temperature, external chemicals, light, electrical fields, and shear stresses, these field responsive gels enable precise control over fundamental material properties, such as swelling, porosity, viscosity, physical structure, and modulus [17]. With this level of external control, numerous applications within medical and industrial fields have moved into the realm of possibility, such as well-controlled drug delivery, inexpensive and accurate biosensors, artificial muscles, smart films/matrices for tissue engineering, immobilization of enzyme and protein, and adsorption of heavy metals [18].

3. Functional soft materials

3.1 Magnetic responsive polymer composites

Magnetic responsive polymer composites are a kind of functional soft materials that respond to weak magnetic stimuli (static or alternating magnetic field) with a significant effect (e.g., movement, heat generation, magnetic or optical signal) [19]. To date, using composites of polymer matrix and magnetic fillers (micro/nanoparticles) is the most elegant and efficient way to obtain magnetic responsive polymer materials exhibiting high amplitude magneto-response. Magnetic responsive polymer composites can be divided into three categories according to their resulting properties: (i) magnetically driven deformation soft materials, including ferrogels, magneto-active or magnetorheological elastomers, which could be deformed (stretching, bending and rotation) in a controlled manner in homogeneous fields or gradients [20]; (ii) magnetically guided materials for magnetic separation and magnetic targeting in the field of biomedical applications, ranging from drug and cell delivery to diagnostic purposes [21]; and (iii) magnetically actuated thermo-responsive materials for remotely controlled drug delivery and shape shifting [22]. Due to their attractive controllable properties, magnetic responsive polymer composites have potential applications in the biomedical, coatings, microfluidics, and microelectronics fields.

3.2 Electronic conductive polymers

Electronic conductive polymers (ECPs) which are polymers with highly π -conjugated polymeric chains take the attractive advantages with the properties of both conventional polymers and electronic properties of metals or semiconductors. Typical conductive polymers consist of polyacetylene, polyaniline, polypyrrole, and polythiophene. Recently, these ECPs have been paid much more attention in polymer research than conventional polymers because of its unique properties, such as excellent conductivity, large surface areas, and shortened pathways for charge/mass transports, similar to that of the large aspect ratio and multifunctional conductive fillers. Different synthetic strategies and issues regarding morphological control methods, such as in-situ polymerization, hard template methods, heteroatom-doping, and so on, have been explored and developed to prepare various conductive polymer nanostructures, which is beneficial to the development of high-performance devices based on these typically nanostructured conductive polymers [23]. With rationally and

desirably designed nanostructure, as a result, these ECPs exhibit excellent electrical, mechanical, and optical properties. Especially, the conductivity of ECPs can be tuned in a wide range up to $10^{-4} \text{ S cm}^{-1}$, although that of neutral conjugated polymers is rather low, usually in the range between 10^{-10} and $10^{-5} \text{ S cm}^{-1}$. Compared with other conventional polymers, the electrical properties of ECPs result from their conductive networks. The electrical properties can be enhanced by the addition of conductive filler, although this procedure leads to poor process-ability and weak mechanical properties [24]. Owing to simple processing tunable properties and easy control of its structure and morphology, ECPs used as one of the most promising candidates in research activities have been studied in wide range of applications, such as energy conversion and storage, sensors, actuators, and biomedical devices [25].

3.3 Thermal conductive polymers

With the development of all classifications of polymers, polymers with high thermal conductivity are of great interest in thermal management systems. Thermal conductive polymers are composed by polymers and filled composites [26]. Polymers have the advantages of good process ability, light weight, low water absorption, high electrical resistivity, high voltage breakdown strength, corrosion resistance, and low cost [27]. Availability of these polymers can expand the plastics industry by partially replacing metals and ceramics in heat transfer devices and systems leading to energy and cost savings. Thermal conductive polymers possess agreeable thermal conductive property. The thermal conductivity of a polymer depends greatly on its morphology and the structure of chains including backbone bonds and side chains, and the inter-chain coupling [28]. What's more, some factors also influence the thermal conductivity of polymers, such as crystallinity, crystal form, orientation of polymer chains, and orientation of ordered domains in both thermoplastics and thermosets were addressed. As for thermal conductive polymers, structure and properties of polymer and fillers (carbon nanotubes, metal particles, and ceramic particles), morphology of the composites, the interaction of polymers and fillers determine the thermal conductivity.

3.4 Bio-medical polymers

Bio-medical polymers as a material intended to interface with biological systems to evaluate, treat, augment or replace any tissue, organ or function of the body, and boundaries for the use of bio-medical polymers are still expanding [29]. The design of new bio-medical polymers is now focused on mimicking many functions of the extracellular matrices of body tissues, as these can regulate host responses in a well-defined manner [30]. However, developing bio-medical polymers with characteristics that could appropriately regenerate tissue or replace the native tissue is a major challenge in this field to date. Recently, naturally derived polymers, such as collagen, alginate, chitosan, and cellulose, have been regaining much attention owing to their inherent biodegradation and biocompatibility, and both physical (roughness, mechanical strength, hydrophobicity, porosity, etc.) and chemical (functionality, drugs, biomolecules, genes, etc.) properties have been modified and their effectiveness were evaluated in performing the desired application, which includes wound healing, drug delivery, tissue engineering applications, and so on [31].

3.5 Semipermeable membrane

A semipermeable membrane is a porous membrane that allows selective diffusion of typical molecules and ions, rather than bio-macromolecules, through

the substance [32]. The semipermeable membrane can be a biofilm or a physical membrane, such as animal bladder membrane, casing, eggshell membrane or an artificial semipermeable membranes as cellophane, collodion membranes, and so on [33]. Whether the substance can pass through the semipermeable membrane primarily depends on the differences in concentration on both sides of the membrane. Generally, it only diffuses from one side of high concentration to the side of low concentration. Besides, it also depends on the particle size of the substance that only particles in smaller diameters than the pore size of semipermeable membrane can pass freely. The semipermeable membrane is mainly used for reverse osmosis and ultrafiltration in membrane separation technology [34]. During the past few decades, semipermeable membranes have been investigated and applied in several different applications, including desalination of saline water, wastewater treatment plants, gas separation plants, fuel cells, etc. The research and applications of semipermeable membranes that transfer heat and water vapor in energy exchangers for building, heating, ventilation, and air-conditioning systems are a new development [35].

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