Proceedings of the 5th International Conference on Materials Chemistry and Environmental Engineering
DOI: 10.54254/2755-2721/130/2025.20462

The Analysis of Conductive Polymer Materials

Xinyue Xu[1,a,*]
[1]*College of Chemistry, Chemical Engineering and Materials Science, Soochow University, Suzhou, Jiangsu, 21500, China*
a. 386248750@qq.com
**corresponding author*

Abstract: In recent years, more and more researchers have begun to focus on the study of conductive polymer materials, which not only breaks the traditional cognition that polymer materials are insulators, but also their excellent performance makes them applicable in many aspects. In this paper, a literature review research method will be used to introduce the classification, conducting mechanism, preparation methods and practical applications of conductive polymer materials, based on the research conducted by scientific researchers in recent years. This paper will also combine relevant literature to provide a forecast of their future development. Through research, the paper finds that conductive polymer materials, as a new type of conductive material, have shown great potential in many fields and have broad development prospects in the future. Currently, conductive polymer materials have made considerable contributions in the fields of electronic devices, flexible electronics, sensing technology, and biomedicine. Although conductive polymer materials have made certain progress in many fields, there are still many challenges to be overcome in their development. In the future, with the development of materials science and nanotechnology, conductive polymer materials will achieve breakthroughs in more fields and achieve more widespread applications.

Keywords: conductive, polymer materials, sensor technology, electromagnetic shielding materials

1. Introduction

With the rapid development of society, the level of science and technology continues to improve, new materials continue to carry out technological innovation, and rapid entry into people’s daily lives has caused their lives to undergo a sea change. At the same time, people's demand for quality of life continues to improve, because the development of science and technology has launched a new challenge, conductive polymer materials. To break traditional polymer materials, which cannot conduct cognition, their excellent performance as a replacement for the traditional metal conductive materials has been widely used.

Polymer materials have long been used as electrical insulators. Until 1977, the Japanese Shirakawa Eiki and other talents found that when silvery films of the semiconducting polymer, *trans* ‘polyacetylene’, (CH)x, are exposed to chlorine, bromine, or iodine vapour, uptake of halogen occurs, and the conductivity increases markedly (over seven orders of magnitude in the case of iodine) to give, depending on the extent of halogenation, silvery or silvery-black films, some of which have a

DOI: 10.54254/2755-2721/130/2025.20462

remarkably high conductivity at room temperature [1]. This is the first conductive polymer material. Later, polypyrrole, polyphenylene sulfide, polyphthalocyanine compounds, polyaniline, polythiophene and so on have been developed into conductive polymer materials. Later, scientists found that using polypyrrole and polyethylene oxide solid-state dielectric film trial production of photovoltaic cells can produce 1mA/cm^2 current and 0.35V voltage. Although this photovoltaic cell is not as good as Si solar cells, the prospects for development are very attractive because the conductive polymers are lighter in weight, easy to form, have a simple process, and can generate a large area of the membrane with the characteristics of the green environment. Conductive polymer materials are also the ideal materials for the production of supercapacitors. Such as the use of doped polypyrrole polymer compounds can make the conductivity up to 100 S/cm. After years of extensive research worldwide, the application of conductive polymers in new energy materials has greatly developed. The paper explores the classification, conducting mechanism, preparation methods and practical applications of conductive polymer materials through a method of literature review based on the research conducted by scientific researchers in recent years. This paper specifically introduces the relevant content of conductive polymer materials, analyzes the current status of conductive polymer materials, research progress, and current challenges, while looking forward to its future development, providing some informative suggestions for this field.

2. Classification and Conduction Principles

Conductive polymer materials are mainly divided into composite and structural conductive polymer materials.

2.1. Composite Conductive Polymer Materials

Composite conductive polymer materials are made from general-purpose polymer materials and various electrically conductive substances using filling, surface or laminated composites. Its performance is closely related to the conductive filler type, dosage, particle size and state, as well as their dispersion state in the polymer material. Commonly used conductive fillers include carbon black, metal powder, metal foil, metal fiber, carbon fiber and so on. The main varieties of such conductive polymer materials are conductive plastics, conductive rubber, conductive fiber fabrics, conductive coatings, conductive adhesives and transparent conductive film.

For composite type, most conducting polymers, such as polyacetylene and polyaniline, contain conjugated π-electron systems, which enable the free movement of electrons and result in electrical conductivity. Conducting polymers can be increased in conductivity by introducing additional electrons or positrons through external dopants. This usually involves the reaction of an oxidizing or reducing agent that changes the charge state in the conductive polymer to form a composite conductive polymer material.

The enhancement of the conductive properties mainly comes from the contribution of conductive nanomaterials. The addition of conductive nanomaterials (such as graphene, carbon nanotubes, etc.) can form a conductive network in the conductive polymer materials to improve the overall conductive properties. These nanomaterials are highly conductive and are capable of forming electron conduction channels, prompting carriers to move throughout the material. The introduction of conductive nanomaterials helps to increase the carrier mobility, i.e., the rate of movement of electrons or positrons in the conductive polymer material. The introduction of conductive nanomaterials improves the conductivity of the entire composite material.

DOI: 10.54254/2755-2721/130/2025.20462

2.2. Structural Conductive Polymer Materials

Structural conductive polymer materials are polymer materials that have an electrically conductive function in the polymer structure itself or after doping. They are a class of polymers with their own properties, which do not need external doping or modification of the conductive medium and can show conduction.

The molecular structure of these types of polymers usually contains organic conjugated structures in which alternating single and double bonds along the polymer chain form a conjugated structure. This structure facilitates the delocalized movement of π-electrons, which allows electrons to move freely through the molecule, thus realizing the conductive properties of the polymer material [2].

3. Preparation and Application

Conductive polymers are widely used in sensor technology, energy storage and conversion, biomedicine, electromagnetic shielding materials, paints and coatings due to their unique conductive properties as well as their plasticity and versatility. The selection of suitable conductive polymer materials, combined with appropriate design and preparation processes, is required in different fields. Suitable conductive polymer materials are selected according to the specific needs of the product. Commonly used conductive polymers include polyacetylene, polyaniline, polythiophene, and polypyrrole. Several fields in which the conductive polymer materials are applied are introduced in the following sections.

3.1. Sensor Technology

Sensors can be divided into physical sensors, chemical sensors, and biological sensors, and are currently used extensively, so the study of conductive polymer materials as an important sensor material has become a hot topic.

In 2014, Rebeca et al. introduced a pressure-microwave sensor based on smart hydrogels-conductive polymers. The study used in situ oxidative polymerization to synthesize conductive polymer nanoparticles from polyamide and then embedded them in thermosensitive hydrogels to form pressure-microwave sensors. The uniform dispersion of polyaniline and other polymers in the hydrogel improved the mechanical properties, allowing the hydrogel to expand to 30,000% of its original volume without being damaged. The experimental results showed that polyaniline would only undergo a phase change in microwave irradiation at $pH < 4$ and when heated, while polypyrrole, which was insensitive to pH, had good sensitivity to microwave radiation at any pH value. Meanwhile, the compressive force applied to the nanocomposite polymer would change its conductivity, which can be used as a pressure sensor, pH switch, temperature switch, microwave control switch, etc. Currently, this sensor has been applied to a drug release system controlled by microwave [3].

In 2012, Patel et al. introduced a chemical sensor element composed of carbon materials and conductive polymer materials, in which the conductive polymer material was formed by combining a high molecular structure material and conductive ion doping to allow steam to pass through with minimal pressure drop, ensuring that the target analytes in the air or pores could pass through the chemical sensor element easily. The sensor responds to the adsorption or desorption process caused by the target analyte's electronic property changes, such as impedance or resistance, and can quickly respond to various target analytes in the environment, making it a high-throughput gas sensor [4].

In 2014, Krupa et al. introduced a novel sensor using expanded graphite-filled copolymers as petroleum sensing materials. Exposure to petroleum causes a change in the sensor's resistance, and the response speed can be adjusted by changing the degree of stretching. Experiments have shown that stretching the sensing membrane by 4% increased the response rate of the sensor by a factor of 12.5 [5]. In 2015, Seyedin et al. first elaborated on large-fiber wet-spun products made from polymer

DOI: 10.54254/2755-2721/130/2025.20462

styrene-isoprene-styrene block copolymer fibers that are both electrically conductive and highly stretchable, which produce a very sensitive response to the magnitude of applied strain that increases with the number of polymer fibers. It was found that the polymer fibers could be blended with commercial spandex yarns to make a highly stable sensor. Such sensors can accurately discriminate against 160% of applied pressure and can be recycled and reused. Combined with a commercial wireless transmitter, this composite braid is highly responsive to bending deformation and is currently being used in personal training and post-injury rehabilitation, while applied research as a remote piezoelectric transducer would also have great potential [6].

Conductive polymers can achieve different conductivity and insulation in stimulated and unstimulated areas by adding composite materials in the field of sensors. They can respond effectively to various stimuli at present. However, their electrical properties are not stable enough, and their response to stimuli is not sensitive enough. Future research should focus on developing stable and sensitive sensors.

3.2. Electromagnetic Shielding Materials

Electromagnetic shielding technology is increasingly gaining attention. Traditional electromagnetic shielding materials include copper, aluminum, and steel. In recent years, scientists have discovered that conductive polymer materials can also be used for electromagnetic shielding.

Longfei Zhang et al. studied using conjugated polyacetylene chains as a replacement for the traditional NIR Aβ probes. The designed probes combined naphthalene or phenyl rings with different numbers of conjugated triple bonds. Six different-length polyacetylene chains were synthesized for the probes. The quantum yield of the probes did not change in different solvent conditions, showing the high affinity and significantly increasing the fluorescence intensity, reaching 45 to 360 times that of conventional probes. Conjugated polyacetylene aggregates can serve as a novel Aβ-type probe for π-conjugated systems, successfully proving their effectiveness in detecting Aβ plaques in vitro. This research addresses a key problem in extending space missions - shielding against the harsh radiation environment encountered in deep space [7].

Deng Yang et al. explored the potential of high-hydrogen-content materials as alternatives to shield against cosmic ray (GCR) particles. Simulations using MULASSIS showed that hydrogen-rich polymer composite materials exhibited good shielding effects against GCR particles. The research results showed that the equivalent dose of these new materials was significantly lower than that of the same face density of aluminum. Polymer composite materials are superior to aluminum. Hydrogen-rich doped polyaniline became the most effective shielding material. Furthermore, increasing the hydrogen percentage in the composite material significantly reduced the production of neutrons, which is a key factor in radiation protection. Incorporating polymer composite materials into the design of shielding materials may lead to the development of more efficient and effective shielding materials.

Robert Moucka et al. investigated the effects of polypyrrole's own properties and the sample preparation process on the shielding effect, and the results showed that the dispersion of PPy nanotubes (PPy-NT) in the silicone matrix and the level of conductivity are crucial for the EMI shielding efficiency, and that high conductivity, as well as the homogeneity of the PPy, can help to improve the shielding effect of the material. Meanwhile, during the sample preparation process, PPy-NT in the silicone matrix has a high shielding effect at a low concentration, but it will reduce the mechanical stability of the sample [8].

As scientists continue to research, more and more conductive polymer materials are being studied for use in electromagnetic shielding, but their performance still needs to be verified, especially their mechanical stability needs to be further improved.

DOI: 10.54254/2755-2721/130/2025.20462

3.3. Biomedical and Environmental Fields

With the scientists' deeper and deeper research, the contributions of conductive polymer materials in the biomedicine and environmental fields are gradually becoming apparent.

Jun Cui et al. developed an eco-friendly self-healing coating for the corrosion protection of water pipes (carbon steel) composed of a polyaniline shell and a core microcapsule structure of SA (mainly polystyrene). The eco-friendly self-healing coating forms a hydrophobic layer on the surface and has good thermal stability, high tensile strength, and good adhesion to carbon steel. In the defective area of the substrate, an SA-CA barrier layer is formed to provide good corrosion protection for the steel. After immersion in water after damage to the coating, no harmful substances were detected, confirming the environmental significance of the coating [9].

Bakhshali Massoumi et al. polymerized dopamine and aniline monomers via chemical oxidation to generate a copolymer of polyaniline-poly(dopamine) (PANI-co-PDA). Then, they polymerized (D,L)-lactide monomer (ROP) to form a novel tri-component polymer. They converted this polymer into nanofiber scaffolds using electrospinning technology, and the scaffolds exhibited excellent physical and chemical (such as mechanical, conductivity, electroactivity, wetting, and morphology) and biological (such as biocompatibility, biodegradability, and enhanced cell adhesion and proliferation performance) properties [10].

Shujun Cui et al. succeeded in achieving a material that maintains electrical conductivity with better mechanical properties by using electrospun polyurethane (PU) and poly(lactic acid) (PLLA) fibers to reinforce a soft polypyrrole (PPy) membrane. The membrane has a multilayer structure but does not lose its shape in aqueous solution, remaining highly flexible and lightweight. This makes the material potentially promising for biomedical applications, such as electrically stimulated cell culture and conductive tissue reconstruction [11].

The potential applications of conductive polymer materials in biomedicine and environmental fields are very broad, such as electrical stimulation of cell culture and conductive tissue reconstruction. Of course, this also depends on the future efforts of scientists.

4. Discussion

Since the development of self-conductive polymer synthesis technology, it has reached a high level of application in developed countries such as the United States and Germany, and its demand is also increasing. The application of conductive polymers in electronic materials and other fields has aroused the attention of scientific researchers around the world to conductive polymer materials. At present, various products developed through the research of conductive polymer materials have achieved success in commerce or the military. In addition to applying conductive polymer composite materials in daily life to improve the conductive polymer material's own properties such as high strength, processability, stability, sensitivity, etc., great progress has also been made.

Most of the research is still in the experimental stage. Although conductive polymer materials have shown good application performance in the experimental process, there are still technical difficulties in transforming them into actual production. Moreover, some materials have low intrinsic conductivity, short service life, high material cost, and poor mechanical properties, which do not meet the rigid requirements in actual applications and have not yet entered people's daily lives. The key to the practical application of conductive polymer materials is to develop conductive materials with excellent comprehensive properties and mechanical strength, fully study the relationship between the structure of conductive polymer materials and their performance, predict their applications based on their unique structure and the unique performance they obtain, and conduct corresponding application research. This is an important aspect of conductive polymer research at present.

DOI: 10.54254/2755-2721/130/2025.20462

Therefore, the trend of the development of conductive polymer materials should mainly focus on the following aspects. First of all, improving their own conductivity and stability to maximize utilization rate and reduce the demand for materials. In addition, enhancing the mechanical properties and processing performance of composite materials through material doping or filling. What's more, functional materials through material doping to make them flame-retardant, acid-resistant, alkali-resistant, and cold-resistant. Moreover, synthesizing self-doped or undoped conductive polymers to solve the stability problem of their polymers. Lastly, exploring new types of conductive polymer materials and studying their unique properties to broaden the scope of application.

5. Conclusion

This paper provides a comprehensive introduction to the classification, conductive mechanism, preparation and application of conductive polymer materials, and looks forward to the future of conductive polymer materials. To some extent, this paper has made some contributions to the research in this field and serves as a reference for future research.

However, there are still some shortcomings in this study, such as the study on the application of conductive polymer materials is not comprehensive enough, and some applications in certain fields have not been covered. In the future, further research will be conducted to have a more thorough understanding of the research and application of this material in various fields.

Although conducting polymer materials are still mostly in the research and testing phase at present, they have already achieved success in the fields of electrode materials and sensors. It is believed that with the unremitting in-depth research of scientific researchers, these problems will be gradually solved, and conducting polymer materials, as a new field in the 21st century, are sure to achieve remarkable achievements in the future.

References

[1] HIDEKI S, LOUIS E J, ALAN G. MacDiarmid, et al.(1988). Synthesis of electrically conducting organic polymers: Halogen derivatives of polyacetylene, (CH)x [J]. Journal of the Chemical Society, Chemical Communications, 578: 1-5.

[2] Fengxian, G. (2017). Design and application of flexible functional polymer materials and devices [D]. University of Science and Technology of China, Hefei.

[3] Ribero R E, Molina M A, Rivarola C R, et al.(2014). Pressure and microwave sensors/actuators based on smart hydrogel/conductive polymer nanocomposite[J]. Sensors Actuators B:Chem, 190(1):270.

[4] Benz M, Patel S V.(2012). Freestanding chemiresistive polymer composite ribbons as high-flux sensors[J]. Journal of Applied Polymer Science, 125(125): 3986.

[5] Krupa I, Prostredny M, Spitalsky Z, et al.(2014). Electrically conductive composites based on an elastomeric matrix filled with expanded graphite as a potential oil sensing material[J]. Smart Mater Struct, 23(12):125020-1.

[6] Seyedin S, Razal J, Innis P C, et al.(2015). Knitted strain sensor textiles of highly conductive all polymeric fibers[J]. ACS Applied Materials & Interfaces, 7(38):21150.

[7] ZHANG L F, GONG X, TIAN C, et al.(2021). Near-Infrared Fluorescent Probes with Rotatable Polyacetylene Chains for the Detection of Amyloid-β Plaques[J]. The Journal of Physical Chemistry B, 125:497-506.

[8] MOUCKA R, SEDLACIK M, PROKES J, et al.(2020). Electromagnetic interference shielding of polypyrrole nanostructures[J]. Synthetic Metals, 269:116573.

[9] CUI J, LI XQ, PEI Z Q, et al.(2019). A long-term stable and environmental friendly self-healing coating with polyaniline/sodium alginate microcapsule structure for corrosion protection of water-delivery pipelines[J]. Chemical Engineering Journal, 358:379-388.

[10] Baknshali, M., Mojtaba A., Rana J.E., et al.(2020). A novel bioinspired conductive, biocompatible, and adhesive terpolymer based on polyaniline, polydopamine, and polylactide as scaffolding biomaterial for tissue engineering application[J]. International Journal of Biological Macromolecules, 147:1174-1184.

[11] Cui, S.J., Mao, J.F., Rouabhia,M., et al.(2021). A biocompatible polypyrrole membrane for biomedical applications [J]. Rsc Advances, 11:16996-17006.