DOI 10.15302/J-SSCAE-2020.05.011

Development Strategies for High-Performance Synthetic Resins in China

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Abstract: High-performance synthetic resins are a key material that supports the development of strategic emerging industries such as advanced manufacturing, new energy, and electronic information. In this study, we investigate the demand for high-performance synthetic resins by industrial development and review the technical development trends of industries in China in terms of high-performance polyolefin resin and other high-performance synthetic resins via literature research and expert consultation. Moreover, we summarize the problems of the industry, including outdated domestic technology and equipment, foreign dependence on several high-end products, insufficient basic research, and inadequate efforts for solving environmental pollution caused by waste plastics. After analyzing the key technologies for high-performance synthetic resins, we propose some industrial development suggestions. High-end products should be developed using existing equipment and technology and subsequently used in large-scale applications. Basic research and personnel training should be strengthened to guarantee technological innovation. Biodegradable plastics should be developed to promote sustainable development. Technical exchange and cooperation between petrochemical enterprises and universities should be enhanced to improve the efficiency of technological transformation and application.
Keywords: high-performance synthetic resins; high-performance polyolefin; industry trend; key technology

1 Introduction

Synthetic resin is one of the three synthetic materials in the world [1] and has been used broadly in agriculture, architecture, automobiles, machinery, electronic information, etc. Synthetic resin is vital to people's lives and societal development. Research regarding high-performance synthetic resins tends to increase their competitive value via improvements in product application, reduction in raw material costs, development of eco-friendly and sustainable products, and improvements in technical service. Research focusing on diversifying raw materials, catalysis techniques, polymerization processes, and large-scale equipment should be conducted. Furthermore, the recycling of waste plastic must be investigated to improve the utilization of plastic. Special synthetic resins such as optical- and electronic-grade synthetic resins should be developed to satisfy demands in high-technology fields.

High-performance polyolefins are one of the development priorities in synthetic resin fields. Recently, catalysis techniques (such as metallocene catalysts), polymerization processes, and polymer processing technologies have developed rapidly. Catalyst design strategies (such as the metal–metal synergistic effect, ligand secondary coordination effect, ligand substrate effect, and redox regulation) [2,3], and new heterogeneous polymerization processes (such as self-stable precipitation polymerization) [4] have been developed to effectively produce high-performance polyolefin materials. High-melt-strength polypropylene, high-density polyethylene pipes,

Received date: July 12, 2020; **Revised date:** September 18, 2020
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Funding program: CAE Advisory Project "Research on New Material Power Strategy by 2035" (2018-ZD-03)
Chinese version: Strategic Study of CAE 2020, 22 (5): 121–127
Cited item: Zhang Liping et al. Development Strategies for High Performance Synthetic Resins in China. *Strategic Study of CAE,* https://doi.org/10.15302/J-SSCAE-2020.05.011

transparent impact polypropylene, and capacitor film made of special materials are examples of breakthroughs in the field of synthetic resin application. Optical-, film-, and electronic-grade synthetic resins and synthetic resins for additive manufacturing have been developing rapidly and applied in high-end fields.

Domestic production of synthetic resin and self-sufficiency have increased steadily in recent years. The application field of synthetic resin continues to expand, and the overall synthetic resin industry development is profitable. However, it is noteworthy that with the increasing capacity and changing demands, structural problems have emerged, including surplus in low-end products and severe shortage in high-end products. Therefore, it is crucial to optimize the industrial layout, strengthen innovation, and focus on the development of high-performance products to promote industrial transformation and upgrading. Herein, technology development trends and problems pertaining to the synthetic resin industry are first discussed; subsequently, suggestions for guiding the development of the synthetic resin industry are provided.

2 Development demand of high-performance synthetic resin

2.1 Significant demand from national emerging strategic industries

According to the *13th Five-Year Plan of National Emerging Strategic Industries* (hereinafter referred to as “the plan”), emerging strategic industries such as new generation information technology and new materials must be developed. As a basic material in advanced manufacturing, high-performance synthetic resin has been incorporated into the plan. Transcending the technical bottleneck of high-performance synthetic resins, upgrading existing material systems, and satisfying the demands of major projects and high-end manufacturing are not only important for cultivating new driving forces and securing future competitive advantage, but also necessary for supporting and extending emerging strategic industries.

2.2 Objective demand of comfortable, healthy, and high-quality life

China’s increasing consumption level and consumption ability has resulted in higher requirements among its people in terms of quality of life. Accordingly, the demand for products made from high-performance synthetic resins has increased, e.g., new eco-friendly products such as safe and nontoxic toys and living products, as well as high-barrier food packaging materials. High-performance synthetic resins can provide more comfort in transportation, e.g., they can be used to produce car interiors with less volatile organic compounds, high-speed rail structural parts, and decoration items that can retard flame, reduce noise, and vibration. Therefore, high-performance synthetic resins are vital to improving people’s quality of life.

2.3 Demand for upgrading high-performance synthetic resin industry

The high-performance synthetic resins industry has not been developed aggressively in China owing to the structural shortage of products. Polyolefin resin yields the largest output and is the most widely used polymer in the current market. However, in China, most products are of the ordinary grade and applied at the low-end level. The consumption of high-end polyolefins (such as metallocene polyethylene, metallocene polypropylene, and higher olefin ethylene copolymer) and special polyolefins (such as ethylene vinyl acetate copolymer (EVA) resin, ethylene vinyl alcohol copolymer (EVOH) resin, and polybutene-1) have reached 1.138×10^7 t/a in China; however, their self-sufficiency is less than 40%. The polyvinyl butyral (PVB) membrane used in interlayer glass, electronic-grade epoxy resins, and polyvinylidene fluoride (PVDF) separators for power batteries is imported [5]. Therefore, under the reformation of China’s chemical industry, high-performance synthetic resins should be developed to upgrade the synthetic resins industry.

3 Technology development trend of high-performance synthetic resin

3.1 High-performance polyolefin

3.1.1 Diversifying raw materials

The diversification of raw materials is important for the future of China’s polyolefin industry. Currently, naphtha is not the only raw material of polyolefins in China. With the emergence of other light hydrocarbon resources, olefin will be important to the polyolefin industry owing to its low cost [6]. For example, the maximum proportion of polyethylene that can be produced from oil is 77%, whereas that from coal is 19%; hence, the latter has become the main method for the capacity expansion of polyolefin. Outsourcing methanol only produces 4% of

DOI 10.15302/J-SSCAE-2020.05.011

polyethylene, and this percentage will continue to decrease in the future. Moreover, raw material diversification in polypropylene production is accelerating, particularly those involving coal and propane. Currently, the capacity of polypropylene from coal is 23%, whereas that from propane dehydrogenation is 8%. Meanwhile, the capacity of polypropylene from oil is reduced by 55% [7]. The key is to guarantee the quality of the raw materials and optimize the feeding control and process to ensure flexibility.

3.1.2 Promoting catalysis technology

Research regarding polyolefin catalysts has focused more on improving the comprehensive nature of the products than on improving the catalytic efficiency [8]. The purpose of further developing catalysts is to promote their ability in controlling the target polymer. Metallocene catalysts can yield a refined regulation of the polymer chain length, branching degree, and stereoregularity. Compared with the traditional Ziegler–Natta catalyst, a metallocene catalyst can improve the quality of polyolefin products in terms of regularity, controllability, and performance [9]. In 2017, a custom-developed metallocene polypropylene catalyst was first used in a batch liquid-phase bulk polypropylene plant (8×10^4 t/a), thereby filling the domestic gap. Owing to their high activity, single active center, and strong copolymerization ability, metallocene catalysts have been developed to control the polymer molecular configuration more accurately and realize customized production. Therefore, research should focus on improving the morphology of metallocene polyolefins such that its molecular weight distribution range can be broadened and the amount of expensive methylaluminoxane can be reduced to further reduce the cost of metallocene catalysts.

In addition, catalyst systems such as palladium diimide, nickel salicylidene, and palladium phosphinosulfonate are being developed, and they have improved the surface properties, adhesion, flexibility, solvent resistance, and rheological properties of polymers as well as increased the solubility and blending with other polymers or polymer additives significantly by catalyzing the copolymerization of polar monomers and olefins.

3.1.3 Coexistence of multiple polymerization processes

In the field of polymerization, multiple types of processes exist, each of which offers its own advantage. Meanwhile, new polymerization processes have emerged. More than 20 types of processes are involved in preparing polypropylene. Among them, solution and slurry methods are obsolete, whereas bulk and gas-phase methods remain favorable, particularly the gas-phase method represented by Unipol, Novolen, and Innovene, which has developed rapidly in the last decade. Additionally, multizone circulating reactors have emerged. The on-site solution polymerization process developed by Dow Chemistry Company and the Exxpol high-pressure polymerization process developed by ExxonMobil Corporation are main polymerization processes used for polyolefin elastomers (POEs). Recently, a new chain shuttle polymerization process has been developed based on the on-site catalyst technique and subsequently used to produce high-performance olefin block copolymers [10,11].

3.1.4 Large-sized production equipment

With the large-scale development of ethylene units and progress in the polyolefin process, the polyolefin unit tends to be large. The production scale of a single device has increased from 2×10^5 t/a to 4×10^5–5×10^5 t/a, and the economy has improved significantly. The total capacity of polypropylene in China exceeds 1×10^7 t/a, and the capacity of a single device exceeds 3×10^5 t/a. The progress in large-scale polyolefin equipment development in China is significant, with the first 2×10^5 t/a polypropylene extrusion granulator made in China destroying the monopoly of foreign companies. In addition, the largest domestic polyethylene extrusion granulator has passed the achievement appraisal and will soon be used in industrial applications.

3.1.5 Emergence of high-grade products

Polyolefin product technology development aims to improve the comprehensive performance of products as well as create new varieties of products, increase their additional value, and expand their application fields. For example, heat-resistant polyethylene developed by improving the co-monomer has been used in building heating. Large-diameter polyethylene pipes with better properties of low sag and cracking resistance developed by optimizing the bimodal polymerization process of polyethylene has been used in oil fields and logistics transportation. New products such as metallocene polyethylene and ultrahigh molecular weight polyethylene for lithium battery separators have been developed. In addition, new products such as polypropylene for medical devices/medical protective products, antibacterial polypropylene, propylene butylene copolymer with low solubility, and low volatile organic compounds polypropylene has emerged.

3.1.6 Emphasis on recycling of waste plastics

Under natural circumstances, plastic products are difficult to decompose after use. Owing to the wide application and short service life of polyolefin plastic products, the recycling of waste plastics has garnered global attention. Waste plastic recycling technologies primarily include direct regeneration, modified regeneration, and chemical recycling. Chemical recycling changes the bonding state of plastic macromolecules through thermal cracking, catalytic cracking, and pyrolysis-catalytic upgrading, which can decompose plastics into various low-molecular-weight compounds or oligomers. These products generated from plastic decomposition can be used to produce fuel oil, fuel gas, and chemical raw materials. Therefore, chemical recycling is the most promising recycling method.

3.2 Other high-performance synthetic resins materials

3.2.1 Optical-grade synthetic resin

Optical-grade synthetic resins, which are primarily used in optical fibers, light emitting diode (LED) lenses, liquid crystal display (LCD) light guide plates, photovoltaic cells, high-end LCD diffusion films, brightening films, touch screen protection films, etc. can be further developed. For optical-grade polyester films, the key is to establish the relationship between the key molding technical indicators and optical properties, improve the existing synchronous biaxial drawing manufacturing equipment, and optimize the online multifunctional precision coating technology [12]. For optical-grade polymethylmethacrylate (PMMA), the key is to improve the impact strength, heat resistance, fluidity, and processability of materials and develop functional materials, such as UV-absorbing PMMA, photochromic PMMA, and other composite materials.

3.2.2 Electronic-grade synthetic resin

Electronic-grade synthetic resins primarily include epoxy, phenolic, and silicone resins. Copper-clad laminates require the highest amount of electronic-grade epoxy resin, followed by semiconductors and integrated circuit packaging materials. Future electronic-grade epoxy resins will be developed to be low cost, flame retardant, heat resistant, high in modulus, eco-friendly, degradable, and composed of composite materials [13]. Furthermore, the development of customized products for copper-clad laminates and electronic packaging will be pursued. Electronic-grade phenolic resins have been primarily used in copper-clad laminates and integrated-circuit packages. With end-use products becoming thinner, multifunctional, high frequency, high speed, and eco-friendly, various high-performance materials must be developed. The performance of phenolic resins can be improved through inorganic element, structural, and blending modifications for developing new products such as benzoxazine resin. Furthermore, silicone resins exhibit excellent thermal oxidation stability, electrical insulation, and can resist moisture, water, rust, cold, ozone, etc. Hence, they are widely used in insulation varnish for H-class motors and transformer coils, semiconductor packaging, electrical parts insulation, etc. Future research should focus on the relationship between the structure and performance of silicone resins, as well as the development of structure-controllable and special silicone resins for chips and circuit boards.

3.2.3 Membrane-grade synthetic resin

Membrane-grade PVB is made from the extrusion molding of 70% PVB resin after plasticizing it with a plasticizer. It is primarily used in laminated safety glass, spacecraft, precision instruments, etc. The raw material quality, production technology, and membrane preparation are key. Currently, the most advanced technique for producing PVB membranes is extrusion salivation. Additionally, multilayer co-extrusion can be used to prepare PVB membranes by compounding new materials in two or more layers of PVB film. This type of PVB membrane offers an advanced functionality of thermal and sound insulation that can be applied to specific fields.

PVDF membranes offer advantages of high mechanical strength, good thermal stability, and strong chemical and water resistance. They can be used in water treatment, medical dialysis, and lithium battery separators. Owing to their high hydrophobicity, they are suitable for hydrophilicity modification. Hence, the modification procedures should be simplified steps and the modification cost reduced such that they can be adapted to industrial applications.

3.2.4 Other synthetic resins

Acrylonitrile butadiene styrene (ABS) resin for additive manufacturing is primarily used in melt extrusion technology in the form of wires. The customized consumption of additive manufacturing has become a global trend, necessitating the development of weather-resistant acrylic styrene acrylonitrile (ASA) resin,

DOI 10.15302/J-SSCAE-2020.05.011

high-heat-resistant ABS, transparent ABS, low shrinkage ABS, and other special materials. Moreover, the mechanical properties and processing properties of the ABS resin can be improved by alloying, compounding, and chemical modification such that it can adapt better to high-end application requirements.

The polyurethane used in high-speed railways exhibits excellent wear resistance, high strength, high elasticity, good impact resistance, fatigue resistance, and low compliance at low temperatures. Therefore, it is widely used in ballastless track filling, ballast glue, elastic pads, waterproof coating, etc. To satisfy the demands of high-speed railways for high-performance materials, it is essential to develop energy-saving and eco-friendly polyurethane production technology as well as master the key production technologies of high-end polyether polyol, high-quality polyester polyol, and new additives.

In terms of high-end special materials for PVC resins, PVC is primarily modified by changing the polymerization methods and performing copolymerization modification to improve its thermal stability and processability [14]. According to the application requirements and performance of plastic products, PVC processing technology and equipment should be optimized to further expand the application range of PVC, e.g., chlorinated polyvinyl chloride for pipes and fittings, paste PVC resin for artificial leather and wallpaper, high-polymerization-degree PVC thermoplastic elastomer resins for medical treatment, cyclohexane -1,2-diisooctyl dicarboxylate plasticized PVC for tracheal intubation, and high cross-linking degree PVC for building sealing strips.

4 Issues concerning development of high-performance synthetic resins in China

4.1 Laggard technology and equipment, low market recognition

The core production technology of some high-performance synthetic resins in China, such as polyvinylidene chloride, is restricted by foreign countries. Therefore, both the technological level and equipment quality must be improved. High-end products in China have undergone the process of development, pilot production, and promotion; however, the production technology remains immature. Furthermore, the quality of products made in China compared with those made in foreign countries is dissimilar. Domestic products generally have low market recognition. For example, enterprises in China tend to use imported polybutene-1 to produce high-end medical devices. The grade of domestic EVA is single and primarily in the middle and low end; therefore, most high-end products still rely on imports. Consequently, the research and development of high-performance synthetic resins in China is stagnant owing to the absence of response from the consuming market.

4.2 Blank domestic technology for high-end products, significant dependence on imports

Using the metallocene polymerization process as an example, China has strived to achieve technological breakthroughs since the 1990s; however, the market demand in terms of catalyst structure design, polymerization process, industrialization scale, and product model remains unsatisfied [15]. The self-sufficiency rate of metallocene polyolefins is less than 30%. Domestic EVOH resin synthesis in China has not yet been industrialized. Although a pilot plant has been built and the products have been trialed, much effort is still required before industrial production can be realized. In addition, the core technology for preparing membrane materials has not been mastered; therefore, products such as high-end PVB films for laminated glass, PVDF binders for power batteries, ion exchange PVDF membranes, piezoelectric films, and dielectric films have been primarily imported.

4.3 Weak basic research, insufficient independent innovation

As China entered the high-performance synthetic resin field relatively late, coupled with low investments in scientific research, the industry weak is lacking in basic research and innovation. The gap between product R&D and application research resulted in the slow promotion and application of new materials, as reflected by the number of patent applications. For example, in terms of global patent applications of epoxy resin for electronic packaging, the proportion of Japanese companies is 68%; American companies, approximately 13%; and Chinese, only 6%. Therefore, the lack of technical achievements directly reflects the lack of independent innovation ability.

4.4 Lack of effort in solving pollution problems caused by plastic waste

As regular synthetic resins are difficult to degrade, the environmental pollution of plastic waste is a serious issue. As such, plastic waste must be recycled and degradable materials developed. China is the largest producer and consumer of plastic worldwide, and its total amount of plastic waste is approximately 4.2×10^7 t/a. Among the plastic waste, package waste constitutes 59%. However, the recycling rate of plastic waste is less than 10%, and the recycling method is primarily physical regeneration, in which the technical content and added value are lower compared with the international approach of combining physical regeneration, energy recovery, chemical reduction, and solid fuel. Furthermore, biodegradable materials are scarce in China; their varieties are few, and their cost high.

5 Key technologies of high-performance synthetic resins

Owing to the potential application of high-performance synthetic resins, the market demand continues to increase. Therefore, China's synthetic resin industry must continue to improve technologically, highlight the development of high-end and functionalization, and further expand the market scale [16]. The development of high-performance synthetic resins primarily includes the following: learning, absorption, and re-innovation during the introduction of foreign high-end equipment and high-end brand production technology; the use of existing equipment and techniques to develop high-end products and optimize the product system; the independent development of key technologies such as new catalyst, polymerization, and processing; and the production of high-end products with independent intellectual property rights.

5.1 New polyolefin catalyst preparation technology

Metallocene catalysts are a key breakthrough in the development of domestic metallocene and the localization of high-end products. Through the breakthrough of catalysts and key supporting technologies, the industrial scale and self-sufficiency rate of metallocene polyolefins (such as hexane-1/octane-1/other α-olefin ethylene copolymer and metallocene polyethylene) with a certain industrial foundation will be further promoted. To realize the functionalization of polyolefins and improve their surface properties, adhesion, flexibility, and compatibility with other materials, new catalytic systems such as palladium diimine, nickel salicylaldiminato, and phosphine acid palladium are key research directions.

5.2 Solution polymerization technology

Solution polymerization offers wide applicability and can be used to produce high-density polyethylene, linear low-density polyethylene, polymer polyols, POE, and α-olefins. The application of a highly active metallocene catalyst can avoid the elution of the catalyst after polymerization, thereby reducing the process energy consumption. Because the reaction must be performed at a high temperature, investigations should focus on the development of catalysts with high temperature resistance, high activity, and high copolymerization ability. Furthermore, the polymerization kinetics, mixing, and heat transfer in the polymerization reactor should be investigated.

5.3 Modification and functionalization technology

High-performance general synthetic resins can be achieved through chemical, structural, and blending modifications, which can improve the mechanical properties, environmental resistance, and processing properties, thereby enabling the launch of multiple brand products. The functional development of synthetic resins should be strengthened to endow them with certain qualities (e. g., ultraviolet absorption, photochromism, etc.) that are demanded for specific applications.

5.4 Advanced processing technology

To achieve multiple functions and compounding in high-performance synthetic resins, it is necessary to extensively investigate the relationship between polymer processing technology and product performance, as well as optimize the processing technology of high-performance synthetic resins, e.g., blending, filling, and reinforcement modification. Moreover, advanced resin matrix composite molding technology and related supporting equipment must be developed to promote the large-scale application of resin transfer molding and film-forming processes, e.g., bidirectional drawing, extrusion casting, and multilayer coextrusion, to achieve a highly efficient, energy-saving, and integrated production processes.

DOI 10.15302/J-SSCAE-2020.05.011

6 Suggestions

6.1 Development of high-end products and realization of large-scale applications using existing equipment and technology

For high-performance polyolefins, catalysts, processes, and processing technologies of high-pressure polyethylene and solution-polymerized polyethylene should be developed the soonest possible. The preparation of metallocene catalysts, large-scale production of trimethyl aluminum, and construction of 10 000 ton metallocene polyolefin production equipment should be realized. Under the current equipment and technology, technological breakthroughs are necessitated for developing high-end polyolefins.

In terms of other high-performance synthetic resins, we must be on par with international progress; develop high-end, different, and specialized products; apply independently developed catalysts, polymerization, and processing technologies on a large scale; and produce high-performance products with independent intellectual property rights (such as electronic-grade epoxy resin and polyvinylidene fluoride) to achieve scaled application domestically.

6.2 Strengthening basic research and talent cultivation to ensure technological innovation

Investment in basic research and application research should be strengthened to accelerate technological breakthroughs in the new generation of polyolefin catalysts as well as enable the precise control of the polymerization reaction, in-situ alloying, and nanocomposites of synthetic resins to achieve high-performance and functionalized synthetic resins. The effects of key molding technologies on the material properties and microstructure should be investigated, and the practical application of high-performance synthetic resins with new structural and composition should be promoted.

Additionally, talent cultivation in the field of high-performance synthetic materials must be emphasized. Based on the advantages of professional disciplines and talent cultivation in universities, we should strengthen the practice in enterprises and form joint training among universities, scientific research institutions, and enterprises to establish a characteristic training system for materials science and engineering talents. We should formulate a talent introduction plan, improve the flexibility of talent introduction, and strengthen the introduction of high-level talents. To provide a favorable environment for the cultivation of innovative teams and talents, we can establish flexible talent management mechanisms, promote the construction of talent teams, as well as encourage and support scientific and technological personnel to undertake innovation and establish enterprises.

6.3 Development of biodegradable plastics to promote sustainable development

The use of biodegradable materials is being pursued in the industry to address waste plastic pollution. With the continuous promotion of plastic restriction and the plastic-ban policy worldwide, the potential demand for biodegradable plastics is significant. As such, research and development, industrialization, and application of biodegradable materials should be emphasized and accelerated to realize the sustainable development of the plastic industry.

Key biodegradable products include polylactic acid, poly (butylene adipate-co-terephthalate), poly (butylene succinate), poly(butylene succinate-co-terephthalate), starch, polylactic-acid-modified polyethylene, and polypropylene.

6.4 Strengthening cooperation between industry, university, research, and application, to improve efficiency of technology transformation and application

Production enterprises should strengthen their cooperation with scientific research institutions, universities, and markets to build a community for research and development. They can jointly develop bottleneck technologies and build a necessary pilot plant to improve the efficiency of transformation.

A number of open and high-level public innovation platforms and innovation alliances should be established, in addition to a state key project and strategic emerging industries (new energy, advanced manufacturing, etc.) oriented toward technology innovation chains that closely connect scientific research, design, engineering, production, and the market.

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