

## Original Paper

# Preparation Methods and Performance Comparison of Common Polymer Films

Yanyu Wang

School of Materials Science and Engineering, Xihua University, Chengdu, Sichuan, 610039, China

### Abstract

*As a crucial component in modern material science and engineering, polymer films are widely applied in various fields such as electronic devices, packaging materials, optical elements, and biomedical products due to their excellent physical, chemical, and mechanical properties. There are numerous preparation methods for polymer films, among which solution casting, spin coating, and hot pressing are the most common. Each method, due to its unique process characteristics and applicable scope, produces films with different properties in terms of thickness uniformity, mechanical strength, optical transparency, and thermal stability. Solution casting is simple and cost-effective, making it suitable for laboratory preparation and large-size film production. Spin coating is widely used in the fabrication of electronic and optical films due to its precise control over film thickness and uniformity. Hot pressing is suitable for rapid film formation of thermoplastic polymers but requires high thermal stability of materials. Different preparation methods significantly influence the structure and properties of the films. Therefore, a systematic performance comparison of these methods is of great significance for guiding rational material selection and process optimization of polymer films. This paper focuses on the common preparation techniques of polymer films, analyzing and comparing them based on their processes and performance indicators, aiming to provide theoretical support and technical reference for the application development and performance improvement of polymer films.*

### Keywords

*Polymer films, Preparation methods, Performance comparison, Solution casting, Spin coating, Hot pressing*

## 1. Introduction

### 1.1 Research Background of Polymer Films

As functional materials with outstanding properties, polymer films have become a major research focus in materials science since the mid-20th century. Due to the structural diversity of polymer chains, polymer films exhibit excellent flexibility, chemical resistance, and low density, making them uniquely advantageous in fields where traditional materials fall short. With continuous advancements in polymer

synthesis and processing technologies, the performance of polymer films has significantly improved, especially in terms of mechanical strength, thermal stability, optical transparency, and electrical properties. Simultaneously, film preparation techniques have become increasingly diverse, evolving from basic methods such as solution casting and spin coating to advanced techniques like hot pressing, spraying, and electrospinning, thereby meeting the specific requirements of different applications. In recent years, driven by the rapid development of microelectronics, flexible displays, solar cells, and biomedical fields, the demand for high-performance functional polymer films has grown significantly. This has led researchers to focus more on the relationship between film structure and properties, as well as optimization of fabrication processes. As a result, the study of polymer film preparation and performance has become a vital frontier in materials science, chemical engineering, and related interdisciplinary fields.

### *1.2 Application Fields of Polymer Films*

Due to their light weight, high toughness, and excellent processability, polymer films play an irreplaceable role in many industries. In the electronics industry, they are widely used in flexible electronic devices, integrated circuit packaging, and display panels, serving as insulating layers, protective films, and dielectric materials to ensure the stability and longevity of devices. In the packaging sector—particularly for food and pharmaceuticals—polymer films with outstanding barrier properties and safety features are preferred, as they ensure product sealing, prevent spoilage, and enhance environmental sustainability. In the optical field, transparent polymer films with adjustable refractive indices are extensively used in anti-reflective coatings, optical filters, and sensors. In biomedicine, polymer films serve as biocompatible materials for artificial organs, drug delivery systems, and tissue engineering scaffolds, promoting the development of medical materials. In the energy sector, such as in solar cells and lithium-ion batteries, polymer films are essential as insulation and protective layers. Therefore, the multifunctionality and designability of polymer films grant them immense value in modern science and industry.

### *1.3 Research Significance and Content Arrangement*

Given the diversity in preparation methods and the significant performance differences among polymer films, systematically studying and comparing the impact of different preparation techniques is of both theoretical and practical importance. On the one hand, gaining deeper insight into the relationship between processing techniques and film structure-performance characteristics helps elucidate microstructural control mechanisms and provides theoretical support for designing novel high-performance films. On the other hand, performance comparisons aid in selecting appropriate preparation methods and materials for practical applications, optimizing manufacturing processes, and improving product quality and application efficiency. This paper focuses on major preparation methods such as solution casting, spin coating, and hot pressing, detailing their principles, operating procedures, and applicable scopes. Emphasis is placed on analyzing how processing conditions affect film mechanical, optical, thermal, and electrical properties. Additionally, the paper summarizes performance

characteristics and optimization strategies of representative polymer film materials, and finally discusses future development trends, aiming to offer scientific insights and technical support for further applications and process enhancements of polymer films.

## **2. Common Preparation Methods of Polymer Films**

### *2.1 Solution Casting Method*

The solution casting method is a classical and widely used technique for preparing polymer films. It mainly involves dissolving polymer materials in suitable solvents to form a uniform polymer solution, which is then cast onto a flat substrate surface. After the solvent naturally evaporates or is accelerated to dry, a uniform and continuous polymer film is obtained. This method is popular due to its simple equipment and flexible process, making it widely applied in both laboratory and industrial production. Solution casting is suitable not only for preparing large-area films but also for controlling film thickness and uniformity relatively well. Additionally, by adjusting the solution concentration, casting speed, and drying conditions, the structure and properties of the film can be tailored. The choice of solvent and processing conditions are critical since the solvent evaporation rate and solubility directly affect the film's surface morphology and internal structure, which in turn determine mechanical and optical properties. In recent years, with the development of green solvents and solvent recovery technologies, the solution casting method has shown good prospects for environmentally friendly material fabrication. Moreover, this method is applicable to various polymer systems such as polyesters, polyamides, and polyurethanes, thus becoming an important technical route for preparing functional films.

#### *2.1.1 Principle of the Method*

The basic principle of solution casting involves utilizing the fluidity of polymer chains in solution and the volatilization characteristics of the solvent. By controlling the solution concentration and casting environment, oriented arrangement and uniform deposition of polymer chains can be achieved. When the polymer solution is cast onto the substrate surface, the liquid forms a continuous film under the effects of surface tension and gravity. As the solvent gradually evaporates, polymer chains precipitate from the solution to form a solid film. The final film thickness mainly depends on solution concentration, casting volume, and substrate size, while the microstructure of the film is influenced by the solvent evaporation rate and drying conditions. Fast-evaporating solvents often lead to pores or rough surfaces, whereas slow evaporation favors molecular chain rearrangement, increasing film density and mechanical performance. By adjusting solution ratios and drying temperatures, solution casting can produce films ranging from amorphous to partially crystalline states to meet different performance requirements. Moreover, stress release and polymer chain rearrangement during casting play decisive roles in the film's optical uniformity and mechanical strength, demonstrating the high potential for process control.

#### *2.1.2 Operating Procedure*

The operating procedure of solution casting typically includes solution preparation, casting, drying, and peeling steps. First, a suitable solvent for the polymer material is selected, and polymer powders or pellets

are dissolved at a specific ratio to prepare a uniform polymer solution, often assisted by magnetic stirring or ultrasound to ensure complete dissolution. Next, the solution is slowly and evenly cast onto a pre-treated smooth substrate surface; the casting amount and speed must be strictly controlled to obtain a uniform liquid film. Then, the substrate is placed in a well-ventilated environment with controlled temperature and humidity for natural drying or accelerated solvent evaporation using heating equipment, while avoiding dust and impurities contaminating the film surface. After drying, if the adhesion between the substrate and the film is moderate, the film can be peeled off mechanically or chemically to obtain a complete and continuous polymer film. The entire process requires strict control of environmental conditions such as temperature, humidity, and airflow, often necessitating clean rooms or drying ovens to ensure film quality. Additionally, parameters are adjusted according to the polymer's properties to ensure the final film meets design requirements.

### 2.1.3 Applicable Materials

The solution casting method is suitable for a wide range of polymer materials, especially linear or branched polymers soluble in common organic or aqueous solvents. Typical applicable materials include polyesters (such as PET), polyamides, polymethyl methacrylate (PMMA), polyvinyl chloride (PVC), and water-soluble polymers like polyvinyl alcohol (PVA). Furthermore, some functional polymers, such as conductive polymers and biodegradable polymers, are also often prepared into films by this method. The solubility of the material and solvent compatibility are key factors determining the suitability of the casting method. For insoluble or poorly soluble polymers, co-solvents or modification treatments are usually required to improve solubility. This method is particularly suitable for preparing films with thicknesses ranging from tens to several hundreds of micrometers, and requires a certain solution viscosity to maintain the stability and uniformity of the cast liquid film. Overall, solution casting is widely applicable in both laboratory research and industrial production, fulfilling the preparation needs of various polymer films.

### 2.1.4 Advantages and Disadvantages

#### (1) Advantages

The greatest advantage of solution casting lies in its simple process and low equipment requirements, suitable for preparing large-area films. Since it is based on solution systems, the operation is flexible, allowing good control of film thickness and uniformity by adjusting solution concentration and casting parameters. In addition, this method is compatible with various polymers, especially complex molecular structures and functional polymers, which facilitates diversified material performance design. Its relatively low preparation temperature avoids thermal degradation of materials, making it suitable for processing thermally sensitive materials. Moreover, solution casting is easy to scale up for industrial production, meeting the consistency requirements of film size and performance. The process also allows easy incorporation of fillers or additives for preparing composite functional films. In summary, solution casting has high applicability and cost-effectiveness in both research and industrial manufacturing.

## (2) Disadvantages

Solution casting also has some drawbacks. Firstly, solvent selection and its evaporation process significantly impact film quality; uneven evaporation may cause surface defects such as pinholes, wrinkles, and thickness non-uniformity. Secondly, slow solvent evaporation leads to longer production cycles, reducing manufacturing efficiency. Some organic solvents pose environmental pollution and safety hazards, necessitating strict emission and recovery systems. Furthermore, the process is sensitive to substrate surface roughness and cleanliness, which may cause unstable adhesion, making film peeling difficult or causing damage. For ultrathin films at the nanoscale, precise thickness control is challenging, resulting in considerable size fluctuations. Additionally, residual solvent in the film may affect thermal stability and mechanical properties. Overall, although solution casting is widely applicable, its limitations must be addressed in the preparation of high-precision and high-performance films.

## 2.2 Spin Coating Method

### 2.2.1 Principle

Spin coating is a film preparation technique where a polymer solution or suspension is deposited onto a substrate that spins at high speed, causing the liquid to spread uniformly under centrifugal force and surface tension, forming a thin film. The principle relies on the combined effects of centrifugal force and surface tension acting on the liquid during rotation, which drives the solution radially outward while the solvent rapidly evaporates, resulting in a uniform and dense polymer film. Spin speed and duration are key parameters influencing film thickness and uniformity; higher spin speeds generally produce thinner, more uniform films. This method is suitable for preparing films with thicknesses ranging from nanometers to micrometers and is widely used in electronics, optics, and biomedical fields. The solvent evaporation rate and solution viscosity during spin coating significantly affect the film's surface quality and internal structure. Due to its efficiency, reproducibility, and low cost, spin coating has become a common technique in laboratories and the semiconductor industry for film preparation.

### 2.2.2 Procedure

The spin coating process typically involves solution preparation, solution dispensing, spinning to form the film, and drying/curing. First, the polymer is dissolved in an appropriate solvent to prepare a homogeneous solution, which is then filtered to remove impurities. A small volume of this polymer solution is dropped onto the center of a clean, dry substrate. Next, the spin coater is activated, and the substrate spins at a set speed, causing the solution to spread outward under centrifugal force, while the solvent evaporates and the film solidifies. Spin times usually range from several seconds to a few minutes and are adjusted according to material and desired film thickness. After spinning, the film often requires further heating or vacuum drying to remove residual solvent and enhance stability and performance. The entire process demands a clean, vibration-free environment to ensure film uniformity and integrity.

### 2.2.3 Applicable Materials

Spin coating is suitable for various polymers, especially linear and branched polymers soluble in low-boiling-point organic solvents. Common materials include polymethyl methacrylate (PMMA), polyvinyl

alcohol (PVA), polyimide (PI), polystyrene (PS), and conductive polymers such as polypyrrole (PPy). This method is particularly effective for producing uniform, thickness-controlled nanofilms, commonly applied in optoelectronic devices, sensors, and biochips. Due to its sensitivity to solution rheology and solvent evaporation rate, solvent ratios and spin parameters need adjustment for different polymer systems. Additionally, substrate surface wettability is critical, often requiring pretreatment to improve film adhesion and uniformity.

#### 2.2.4 Advantages and Disadvantages

##### (1) Advantages

Spin coating offers simplicity, rapid film formation, and high reproducibility. It enables precise thickness control by adjusting spin speed and duration, producing films from tens of nanometers to a few micrometers thick. Films formed by spin coating are smooth and uniform, meeting the stringent uniformity requirements of optical and electronic devices. The equipment is compact and flexible, suitable for quick laboratory preparation and process development. Material waste is minimal, and multilayer film structures can be conveniently fabricated. Overall, spin coating is cost-effective and practical in the thin-film fabrication field.

##### (2) Disadvantages

The main limitation of spin coating is the small achievable coating area, which restricts its use for large-area films. Due to centrifugal forces, film thickness often shows a gradient from center to substrate edge, limiting uniformity for thick films. It is also limited by substrate size and shape, typically suitable only for flat or slightly curved surfaces. Rapid solvent evaporation can induce internal stresses, causing film cracking or wrinkling. For high-viscosity solutions or multi-component systems, controlling flow during spinning is challenging and may affect film quality. Environmental factors like airflow, temperature, and humidity significantly impact film properties, requiring strict control over the fabrication environment.

### 2.3 Hot Pressing Method

#### 2.3.1 Principle

The hot pressing method is a film fabrication technique that involves softening or melting polymer materials under high temperature and pressure, followed by molding the material into thin films using a mold. This method takes advantage of the increased molecular chain mobility and softened state of thermoplastic polymers when heated above their glass transition or melting temperatures. Under mold pressure, the material is pressed into thin films of the desired thickness, and then cooled to solidify, forming dense and uniform film layers. The hot pressing process emphasizes the coordinated control of temperature and pressure to ensure film density and mechanical properties. This technique boasts high production efficiency and excellent film quality, making it suitable for large-scale industrial applications, especially in polymer composites and multilayer film fabrication.

#### 2.3.2 Procedure

The hot pressing process includes four main steps: material preparation, heating, pressing and molding, and cooling and demolding. First, the polymer material is pre-processed into suitable forms such as sheets,

pellets, or powders. Next, the material is placed in a hot press mold and heated to a predetermined temperature to soften or melt the polymer. Then, pressure is applied to evenly spread the material into a thin film, maintaining the pressure for a certain time to eliminate internal bubbles and defects. After molding, the film is cooled under pressure to solidify and fix its shape. Finally, the film is demolded and may undergo further surface treatment or trimming as needed. Precise control of temperature and pressure throughout the process is critical, and automated equipment is commonly used to ensure film quality and production efficiency.

### 2.3.3 Applicable Materials

The hot pressing method is mainly suitable for thermoplastic polymers such as polyethylene (PE), polypropylene (PP), polyamide (PA), polycarbonate (PC), and polyvinyl chloride (PVC). It is especially effective for polymers with strong crystallinity and clear melting points, allowing the control of crystallinity and mechanical properties of the films through hot pressing. This method is also applicable to composite polymers containing fillers, making it ideal for producing functionally enhanced films. For thermosetting polymers, which cannot be melted, hot pressing is generally limited to the semi-softened stage or is used indirectly through composite technologies. Overall, hot pressing is well-suited for mass production due to its thermal-mechanical characteristics, with relatively easy control over film thickness and structural uniformity.

### 2.3.4 Advantages and Disadvantages

#### (1) Advantages

Films produced by hot pressing exhibit high density, excellent mechanical properties, and fast forming speed. The process does not require solvents, avoiding residual solvent issues and environmental concerns, making it suitable for green manufacturing. Hot pressing enables effective control of film thickness and uniformity, supporting industrial-scale production of large-area films. By adjusting temperature and pressure, it can also modulate the material's crystalline structure, enhancing thermal stability and mechanical strength of the films. Moreover, hot pressing technology is mature, with standardized equipment and relatively low production costs, suitable for scale-up. It also facilitates multilayer composite film fabrication and functional processing, broadening the application scope of films.

#### (2) Disadvantages

The main drawbacks of hot pressing include high equipment investment and complex process parameter control, requiring skilled operation and advanced machinery. Some polymers may undergo thermal degradation or cross-linking reactions under high temperature and pressure, affecting film quality. The method is unsuitable for thermosetting polymers or materials that cannot be melted, limiting the range of applicable materials. Achieving extremely thin films is challenging due to equipment and process constraints, making nanoscale thickness control difficult. Uneven cooling rates during hot pressing may cause internal stress in the films, impacting their mechanical stability. In summary, while hot pressing is excellent for large-scale industrial production, it has limitations in high-precision and multifunctional

film fabrication.

#### *2.4 Other Preparation Methods*

In addition to the main preparation methods described above, various other polymer film fabrication techniques have gradually developed and are applied in specific fields.

The spraying method involves uniformly spraying a polymer solution or suspension onto a substrate in the form of a mist. This technique is suitable for preparing films with complex shapes or large areas and is widely used in coatings and protective films.

The stretching method mechanically stretches pre-made film materials to adjust the orientation of molecular chains, thereby enhancing the mechanical strength and anisotropic properties of the films. It is commonly used in high-strength packaging materials.

Electrospinning technology uses a high voltage to draw polymer solutions into nanofibers, producing nanofiber membranes with a high specific surface area and excellent porous structures. This method is widely applied in filtration, sensing, and biomedical fields.

Each method, due to its unique processing characteristics and suitable materials, imparts different performance advantages to the films, enriching the fabrication techniques and application prospects of polymer films.

### **3. Influence of Different Preparation Methods on Film Properties**

#### *3.1 Mechanical Properties*

##### *3.1.1 Tensile Strength*

Tensile strength measures a polymer film's ability to resist breaking under stretching forces and is a key indicator of the film's mechanical performance. Different preparation methods significantly affect the molecular chain arrangement and internal structure of the film, thereby influencing its tensile strength. Films prepared by solution casting typically exhibit relatively low tensile strength because the slow solvent evaporation allows molecular chains more freedom, resulting in a looser internal structure. Spin coating, due to the centrifugal force during rotation, promotes molecular chain alignment and forms dense films, generally producing films with higher and more uniform tensile strength. The hot pressing method, under high temperature and pressure, enables tighter molecular packing and crystallization, enhancing the film's mechanical strength and durability. Moreover, the presence of defects such as bubbles and cracks, influenced by different methods, indirectly affects the stability of tensile strength. Overall, films prepared by hot pressing show clear advantages in tensile strength, while spin coating offers more precise control over film thickness and uniformity. Choosing an appropriate preparation method should be based on specific application requirements.

##### *3.1.2 Elongation at Break*

Elongation at break reflects a polymer film's ability to stretch and deform before breaking, indicating its flexibility and toughness. The preparation method directly affects the molecular chain orientation and defect distribution inside the film, thus influencing elongation at break. Films made by solution casting



usually have higher free volume and lower crystallinity, resulting in better ductility and higher elongation at break. In contrast, hot pressing promotes high crystallinity and dense packing of molecular chains due to high temperature and pressure, which increases strength but reduces flexibility, leading to generally lower elongation at break. Spin-coated films exhibit elongation at break values between these two methods, and their properties are strongly influenced by rotation speed and solvent evaporation rate. For applications requiring high flexibility and fatigue resistance, such as flexible electronics and stretchable sensors, selecting a preparation method that yields high elongation at break is crucial. In summary, different fabrication techniques demonstrate the typical trade-off between strength and flexibility in polymer films.

### 3.2 Optical Properties

#### 3.2.1 Transmittance

The transmittance of polymer films is an important parameter measuring optical transparency, directly affecting their performance in optical and display devices. Preparation methods significantly impact the film's surface smoothness, internal defects, and crystallinity, thereby influencing light scattering and absorption. Films prepared by solution casting usually have relatively high transmittance due to the slow solvent evaporation leading to a more uniform amorphous structure; however, controlling film thickness is difficult, and thicker films may reduce transmittance. Spin coating forms extremely uniform and smooth films driven by centrifugal force, resulting in high and consistent transmittance, making it suitable for preparing highly transparent films required in optoelectronic devices. Films made by hot pressing have higher crystallinity, which increases scattering at crystal boundaries and results in relatively lower transmittance but better weather resistance and mechanical strength. Environmental factors during preparation, such as humidity and temperature, also affect surface and internal uniformity, further influencing transmittance. Overall, spin-coated polymer films exhibit superior performance in transmittance.

#### 3.2.2 Refractive Index

The refractive index is an important optical property that determines how a film refracts and reflects light. It is influenced by the molecular structure, density, and crystallinity of the material, which are indirectly controlled by the preparation method. Solution casting generally produces films with looser amorphous structures and relatively lower density, resulting in a smaller and more uniform refractive index. Spin-coated films have more regularly arranged molecular chains and higher density, leading to an increased refractive index and better uniformity, suitable for optical coatings and waveguide materials. Hot pressing promotes crystallization and tight molecular packing under high temperature and pressure, significantly increasing the refractive index, but may also induce internal stresses that affect optical stability. Precise control of the refractive index is crucial for applications such as optical filters, mirrors, and displays. Therefore, selecting the appropriate preparation process to tailor the optical refractive properties of films is key to designing high-performance optical polymer films.

### 3.3 Thermal Properties

#### 3.3.1 Thermal Stability

Thermal stability refers to the ability of a film to maintain its structure and performance without significant degradation under high-temperature conditions. Different preparation methods indirectly determine the thermal stability of the film by affecting its crystallinity, molecular chain arrangement, and defect distribution. Films prepared by hot pressing exhibit higher thermal stability due to the promotion of crystallization and tight molecular packing under high temperature and pressure, enabling them to withstand higher operating temperatures. In contrast, solution-cast films have lower crystallinity and relatively poorer thermal stability, making them prone to softening and deformation at elevated temperatures. Spin-coated films, formed rapidly, contain fewer internal defects but tend to be thinner and may retain residual solvents, which can reduce thermal stability. Temperature control during preparation and post-treatment processes such as annealing can effectively improve the film's thermal stability. High thermal stability polymer films are widely used in electronic packaging, high-temperature protection, and aerospace fields, making the optimization of preparation processes particularly critical.

#### 3.3.2 Glass Transition Temperature ( $T_g$ )

The glass transition temperature ( $T_g$ ) is the critical temperature at which a polymer material transitions from a glassy state to a rubbery state, reflecting changes in molecular chain mobility. Preparation methods influence the film's microstructure and segmental mobility, thus affecting  $T_g$ . Films produced by solution casting tend to have higher segmental mobility due to slow solvent evaporation, resulting in a relatively lower  $T_g$ . Spin-coated films, with more orderly molecular chain arrangement and denser layers, show an increased  $T_g$ . Hot pressing, through high temperature and pressure, tightly packs and crystallizes molecular chains, significantly raising  $T_g$  and enhancing the film's thermo-mechanical performance. Additionally, residual stress and solvent residues during preparation also affect  $T_g$  measurements and actual behavior. Selecting suitable preparation methods and process parameters aids in designing polymer films that meet high-temperature application requirements.

### 3.4 Electrical Properties

#### 3.4.1 Dielectric Constant

The dielectric constant reflects a material's ability to store electrical energy and is an important electrical parameter for polymer films in electronic devices. Preparation methods influence the film's density, crystallinity, and defect content, thereby determining dielectric properties. Films prepared by solution casting generally have an amorphous structure with higher porosity, resulting in a lower and less uniform dielectric constant. Spin-coated films, being uniform and dense, exhibit higher and more consistent dielectric constants, suitable for capacitors and insulating layers. Hot pressing enhances crystallinity and film density through high temperature and pressure, further improving the dielectric constant; however, excessive crystallinity may sometimes cause electrical instability. The molecular structure and presence of polar groups in the material are also closely related to dielectric performance. Controlling film purity and uniformity during preparation directly impacts the final electrical properties.

### 3.4.2 Insulation Performance

Insulation performance reflects a polymer film's ability to prevent current flow and is a key indicator for insulating layers in electronic components. Different preparation methods significantly affect film uniformity, defect quantity, and impurity content, thus influencing insulation performance. Solution-cast films often suffer from incomplete solvent evaporation and residual impurities, leading to reduced insulation performance. Spin-coated films, being uniform, dense, and low in impurities, exhibit excellent insulation properties, especially suitable for high-frequency electronic devices. Hot pressing improves crystallinity and density, helping reduce leakage current and dielectric loss, thereby enhancing insulation strength; however, excessive crystallinity may cause film brittleness. To enhance insulation performance, strict control of process parameters and post-treatment such as vacuum drying and annealing are necessary to ensure film purity and uniformity.

## 3.5 Surface Properties

### 3.5.1 Surface Roughness

The surface roughness of polymer films directly affects their optical performance, adhesion, and functionality in various applications. Preparation methods influence surface morphology by controlling the film formation dynamics and solvent evaporation rate. Solution casting, due to the slow evaporation of solvents, often results in films with relatively large particles or uneven crystallization on the surface, leading to higher surface roughness. Spin coating utilizes high-speed centrifugal force to promote uniform spreading of the film, producing a smooth and flat surface with the lowest surface roughness among the methods. Hot pressing, conducted under high temperature and pressure, yields a dense surface structure with roughness between that of solution casting and spin coating; however, internal stresses during hot pressing may induce micro-cracks on the surface. Controlling surface roughness is critical for manufacturing optical devices, improving coating adhesion, and functionalizing biomedical films. Therefore, selecting an appropriate preparation technique and optimizing processing parameters is essential.

### 3.5.2 Hydrophobicity/Hydrophilicity

The hydrophobic or hydrophilic nature of a film determines its wetting behavior and interfacial interactions in various environments. Preparation methods affect surface energy and wettability by regulating the film's surface chemical composition and microstructure. Solution casting, with its slower film formation process, tends to produce uniform films exhibiting stronger hydrophilicity, making it suitable for biomedical applications. Spin-coated films, due to their smooth surfaces and possible introduction of low surface energy groups, generally display strong hydrophobicity, which is favorable for waterproof coatings and electronic packaging. Hot pressing, by adjusting temperature and pressure, can modify surface microstructure and the exposure of functional groups, thereby tuning the hydrophobic/hydrophilic balance. Considering the application environment and functional requirements comprehensively, choosing the right preparation method is key to achieving tailored surface properties.

## 4. Typical Polymer Film Materials and Their Preparation Process Examples

### 4.1 Polyester Films (PET, PEN)

#### 4.1.1 Preparation Methods and Parameters

Polyester films mainly include polyethylene terephthalate (PET) and polyethylene naphthalate (PEN), which are widely used in packaging, electronics, and optical fields. PET films are typically prepared by melt extrusion, where polyester pellets are heated above 300°C to melt, extruded through a die to form films, then subjected to traction, stretching, and annealing to optimize molecular orientation and crystallinity. Key parameters include extrusion temperature, stretch ratio, cooling rate, and annealing temperature, with stretch ratios usually between 3-5 times and annealing temperatures controlled between 90-120°C. PEN film preparation is similar to PET but requires slightly higher temperatures due to the more rigid PEN molecular chains; temperature gradient control during stretching is emphasized to avoid film breakage. Additionally, solution casting and spin coating are also used to prepare highly transparent and uniformly thick PET/PEN films, especially for electronic display devices.

#### 4.1.2 Performance Characteristics

PET and PEN films are known for excellent mechanical strength, good thermal stability, and high transparency. PET films exhibit high tensile strength, moderate elongation at break, good dielectric properties, chemical resistance, and environmental aging resistance, making them suitable for capacitor substrates and food packaging. PEN films, containing rigid benzene rings in their molecular structure, show higher thermal and dimensional stability, with glass transition temperatures above 120°C, and excellent radiation and UV resistance. Optically, PET and PEN films have high light transmittance and stable refractive indices, suitable for flexible displays and photovoltaic cell encapsulation. Overall, polyester films combine good mechanical, thermal, and optical properties, making them among the most widely used polymer film materials today.

### 4.2 Polyimide Films (PI)

#### 4.2.1 Preparation Methods and Parameters

Polyimide (PI) films, due to their outstanding high-temperature resistance and electrical insulation properties, are widely used in electronics, electrical engineering, and aerospace fields. PI films are generally prepared by solution casting. First, polyamic acid (PAA) precursor solutions are synthesized by reacting diamines and dianhydrides in polar solvents, then cast into films and subjected to stepwise thermal curing to convert to polyimide. Typical thermal treatment includes pre-drying at 80°C, solvent removal at 150°C, and gradual curing from 300°C to 400°C to ensure full imidization and achieve high molecular weight and stable structure. Spin coating is also studied for producing ultrathin PI films, with parameters such as spin speeds (1000-4000 rpm) and solvent evaporation control. Melt extrusion is less common due to PI's high melting point.

#### 4.2.2 Performance Characteristics

PI films exhibit extremely high thermal stability, able to withstand continuous operating temperatures above 400°C, with glass transition temperatures around 350°C. Mechanically, PI films show excellent

strength and toughness with relatively high elongation at break, suitable for fatigue-resistant flexible circuit boards. Their low dielectric constant and excellent insulation make them ideal insulating materials. Optically, PI films typically appear yellow to amber with generally lower transparency, though transparency can be improved by modification and copolymerization. Surface hydrophobicity is moderate, aiding environmental adaptability. Because of these comprehensive excellent properties, PI films are widely used in flexible electronics, solar cell encapsulation, and high-temperature insulation materials.

#### *4.3 Polyethylene Films (PE)*

##### *4.3.1 Preparation Methods and Parameters*

Polyethylene (PE) films are among the most common plastic films and are mainly produced by blow molding and extrusion. Blow molding extrudes molten PE polymer into a tubular film, which is inflated by air to form a thin film, then cooled and drawn. The blowing ratio and stretching rate control film thickness and properties. Typical processing temperatures range from 120-250°C, with blowing ratios between 2-4 times. Extrusion involves direct extrusion of flat films through a die followed by cooling and film formation; parameters include extrusion speed, cooling rate, and stretch ratio. Solution methods are less common. High-density PE (HDPE) and low-density PE (LDPE) differ in molecular structure, affecting processing parameters and performance.

##### *4.3.2 Performance Characteristics*

PE films are favored for their excellent flexibility and chemical resistance. HDPE films have higher density and crystallinity, resulting in better mechanical strength and wear resistance but poorer transparency. LDPE films are more flexible, have higher elongation at break, and better light transmittance, often used for packaging and agricultural mulch films. PE films have relatively low thermal stability, with use temperatures generally below 100°C. Electrically, PE exhibits good insulation and low dielectric constant. Due to their good mechanical properties and cost advantages, PE films are widely used in packaging, insulation, electrical protection, and agricultural films.

#### *4.4 Polymethyl Methacrylate Films (PMMA)*

##### *4.4.1 Preparation Methods and Parameters*

Polymethyl methacrylate (PMMA) films are usually prepared by solution casting and spin coating. In solution casting, PMMA is dissolved in organic solvents such as toluene or dichloromethane, uniformly cast on a flat substrate, and allowed to form a film by solvent evaporation. Spin coating spreads the solution evenly via high-speed rotation, with film thickness and uniformity controlled by spin speed and solution concentration, typically in the range of 1000-5000 rpm. Temperature control and drying speed during preparation significantly affect surface smoothness and mechanical properties. Hot pressing is less common due to PMMA's thermoplastic nature, favoring solution methods.

##### *4.4.2 Performance Characteristics*

PMMA films have excellent optical transparency with light transmittance over 92%, making them ideal transparent materials. They exhibit moderate mechanical strength, high hardness, relatively low

elongation at break, are brittle but easy to process and form. Thermally, PMMA has a glass transition temperature around 105°C, with better heat resistance than many common plastics. Electrically, PMMA has good dielectric properties with low dielectric constant and stable insulation. Surface hydrophobicity is moderate, and the surface can be easily modified to adjust wettability. PMMA films are widely used in optical lenses, display protective films, and high-transparency packaging materials, representing a typical material in the high-transparency film category.

## **5. Strategies for Optimizing the Performance of Polymer Films**

### *5.1 Performance Improvement through Process Optimization*

#### **5.1.1 Temperature Control**

Temperature control is a critical factor affecting the performance of polymer films during their fabrication process. The processing temperature directly influences the mobility of polymer chains, crystallization behavior, and internal stress distribution, thereby determining the mechanical strength and thermal stability of the film. Excessively high temperatures may cause excessive molecular motion and thermal degradation, reducing mechanical properties and heat resistance; conversely, too low temperatures restrict molecular motion, decrease crystallinity, and result in defects and brittleness in the film.

In solution casting and spin coating methods, controlling the solvent evaporation temperature directly affects the uniformity and surface quality of the film. In hot pressing methods, temperature is also crucial for densification and molecular orientation of the film. By precisely adjusting the temperature profile and ensuring uniform heating, highly ordered molecular chain alignment can be achieved, significantly enhancing tensile strength and thermal stability, thus optimizing film performance.

#### **5.1.2 Solvent Selection**

The type of solvent and its evaporation rate have significant effects on the film formation process and the final properties of polymer films. Selecting an appropriate solvent ensures complete dissolution of the polymer and improves solution homogeneity, while also regulating film formation speed and structural development.

Too rapid solvent evaporation tends to cause surface roughness, pores, and stress concentration, degrading mechanical strength and optical transparency; too slow evaporation may lead to uneven film thickness and crystallization defects. The ratio of polar to non-polar solvents and the design of mixed solvent systems can optimize polymer chain arrangement and the film's microstructure, enhancing thermal and mechanical properties. Modern fabrication techniques achieve high-quality films by finely tuning solvent systems combined with temperature control, improving application adaptability.

#### **5.1.3 Annealing Treatment**

Annealing, as a post-processing method, can significantly improve polymer film crystallinity and molecular orientation, thus enhancing mechanical properties and thermal stability. Proper annealing temperature and time help relieve internal stresses generated during film fabrication and promote rearrangement and perfection of polymer chain segments and crystalline structures.

Annealing is typically performed above the glass transition temperature but below the melting point, with time optimized based on material properties and film thickness. It also enhances optical uniformity and electrical performance, reduces defects and impurities, and improves weather resistance. Different polymers exhibit varied sensitivity to annealing conditions, making careful design of annealing processes essential for producing high-performance films.

## *5.2 Blending and Composite Material Techniques*

### *5.2.1 Introduction of Nanofillers*

Incorporating nanofillers is an effective strategy to enhance polymer film performance. Nanomaterials such as nanoclays, carbon nanotubes, graphene, and nano-oxides possess high specific surface area and excellent mechanical and thermal properties, significantly improving the strength, modulus, and thermal stability of the films.

Uniform dispersion of nanofillers in the polymer matrix can hinder polymer chain mobility, increase crystallinity and dimensional stability, and improve barrier and corrosion resistance. The morphology, size, and interfacial bonding state of fillers greatly influence composite film properties. Good interfacial compatibility is key to performance enhancement. Surface-modified nanofillers can strengthen interactions with polymer chains, improving uniformity and mechanical performance of composite films.

### *5.2.2 Performance Enhancement of Composite Films*

Polymer films prepared by blending and composite techniques exhibit comprehensive properties superior to single-component materials due to synergistic effects. Composite films can achieve multi-dimensional improvements in mechanical strength, thermal stability, wear resistance, and barrier properties.

For example, combining flexible polymers with rigid nanofillers maintains film toughness while enhancing strength; or designing multilayer composite structures integrates different functional layers to meet specific application requirements. Composite processes include melt blending, solution blending, and lamination, where selection of appropriate techniques and parameters is crucial for optimal results. The development of composite technologies has greatly expanded the application range of polymer films and promoted innovation in functional film materials.

## *5.3 Surface Modification Techniques*

### *5.3.1 Plasma Treatment*

Plasma treatment is a common surface modification technique for polymer films. High-energy plasma excitation induces chemical and physical changes in the film surface molecular structure, increasing surface energy and hydrophilicity. This method effectively introduces active groups, improving adhesion and wettability, thus enhancing bonding with subsequent coatings or adhesives.

Plasma treatment parameters include power, gas type, and treatment duration; proper control achieves surface functionalization without damaging the bulk structure. This technology is widely applied in flexible electronic packaging, biomedical films, and optical films to optimize surface performance and is considered a green and environmentally friendly process.

### 5.3.2 Chemical Modification

Chemical modification involves introducing specific functional groups or crosslinkers to alter the surface properties of polymer films, enabling functions such as hydrophobicity, hydrophilicity, self-cleaning, or antibacterial activity. Common methods include surface graft polymerization, coupling agent treatment, and surface crosslinking.

Chemical modification not only improves surface wettability but also enhances mechanical strength, wear resistance, and environmental adaptability. By designing reaction pathways and conditions, precise control of surface properties can be achieved to meet industrial demands for functional films. Recently, green chemical modification methods such as photo-initiated graft polymerization have gained wide attention, promoting sustainable development of polymer film surface functionalization.

## 6. Conclusion and Outlook

### 6.1 Main Conclusions

This paper systematically reviews common preparation methods for polymer films and their performance differences. Solution casting, spin coating, and hot pressing each have unique characteristics suitable for different polymer materials and application requirements. Process parameters such as temperature, solvent selection, and annealing treatment significantly affect the mechanical, optical, thermal, electrical, and surface properties of films. The incorporation of nanofillers and composite techniques effectively enhances the comprehensive performance of films, while surface modification techniques such as plasma treatment and chemical modification further improve film functionality and environmental adaptability. Through reasonable process optimization and material design, polymer films have broad application prospects in electronic devices, packaging materials, optical components, and medical fields. In summary, the close relationship between preparation methods and performance provides a theoretical basis and technical path for directional design and functional improvement of polymer films.

### 6.2 Existing Problems

Despite continuous advancements in polymer film preparation technologies, many challenges remain. First, controlling film uniformity and defects during preparation is difficult, especially for large-area and thickness-controllable films, which have yet to reach ideal levels. Second, different preparation methods have limitations in achieving complex functionalities and struggle to meet multifunctional integration demands. Additionally, issues related to nanofiller dispersion and interfacial compatibility restrict further performance enhancement of composite materials. Although surface modification techniques are abundant, their long-term stability and environmental friendliness still need improvement. Lastly, reproducibility of preparation processes and industrial scalability face technical bottlenecks, requiring a balance of cost, efficiency, and performance.

### 6.3 Future Development Trends and Research Directions

The future development of polymer films will increasingly emphasize intelligence and multifunctionality. New preparation techniques such as 3D printing, in situ polymerization, and self-assembly methods are



expected to achieve more precise structural control and performance regulation. The combination of nanotechnology and bio-based materials will promote the development of environmentally friendly and biodegradable films. The design of functional composite films will break the limitation of single performance, achieving synergistic optimization of mechanical, optical, and electrical properties. Meanwhile, green, low-energy consumption processes and sustainable manufacturing technologies will become research hotspots. In surface modification, smart responsive and self-healing films will be widely applied in flexible electronics, biomedicine, and environmental monitoring fields. Overall, integrating advanced material science with innovative preparation technologies, polymer films will play an increasingly important role in high-tech industries.

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