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Development and Die-Cutting Process Optimization of High-Temperature-Resistant and Anti-Aging Barcode Substrate for Photovoltaic Modules

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Abstract

This study addresses the durability issues of barcode substrates for photovoltaic (PV) modules under extreme conditions such as high temperature, high humidity, and intense ultraviolet (UV) radiation. A three-layer structured barcode substrate with high-temperature resistance and anti-aging properties was developed, and the die-cutting process was optimized. The three-layer structure consists of a polyethylene terephthalate (PET) substrate layer, a polyimide (PI) anti-aging layer, and a wear-resistant coating. The synergistic effect of these layers significantly enhances the substrate's temperature resistance and anti-aging performance. Experimental results indicate that after 100 thermal cycles, the tensile strength retention rate of the three-layer structured substrate reaches 92%, much higher than the 65% of traditional PET substrate. After 1000 hours of UV irradiation, the color difference (ΔE) is only 1.5, compared to the 4.0 of traditional PET substrate. Following the optimization of the die-cutting process, the burr rate was reduced from 8% to 0.5%, and the material utilization rate increased from 82% to 95%. In the pilot application at Mingyang Smart and the long-term testing in desert power stations, the three-layer structured barcode substrate demonstrated excellent performance, with a barcode integrity rate of 98%, significantly higher than the 70% of traditional PET substrate. This study provides significant technical support for the development of barcode substrates for PV modules, promoting the high-quality development of the PV industry.

Keywords: photovoltaic modules, high-temperature-resistant and anti-aging barcode substrate, three-layer structure, die-cutting process optimization, temperature resistance, anti-aging properties, die-cutting precision, material utilization rate, extreme environment, PV industry, production efficiency, reliability, traceability system

1. Introduction

1.1 Demand for Barcode Substrate in the PV Industry

1.1.1 Development of the PV Industry and the Importance of Barcode Substrate

With the increasing global demand for clean energy, the PV industry, as an important part of renewable energy, has experienced rapid growth in recent years. According to statistics from the International Energy Agency (IEA), the global PV installed capacity has increased nearly 20-fold over the past decade, and it is projected that by 2030, the global cumulative PV installed capacity will exceed 3000 gigawatts. In this process of rapid development, PV modules, as the core components of PV systems, directly affect the power generation efficiency and service life of the entire PV power station.

1.1.2 Requirements for Barcode Substrate in the "14th Five-Year Plan" for PV Industry Development

The "14th Five-Year Plan" for PV Industry Development sets high standards and refined trends for barcode substrates. As a key part of PV modules, barcode substrates need to maintain stable performance in extreme environments. Their high-temperature resistance and anti-aging capabilities are crucial. They must ensure that barcode information remains clearly readable within the temperature range of -40℃ to 120℃ throughout the 25-year service life of the modules. This is of great significance for ensuring the long-term stable operation and traceability of PV modules. Meanwhile, the high-precision die-cutting adaptability of barcode substrates is also indispensable. It can not only improve production efficiency but also effectively reduce costs, minimize material waste, and enhance die-cutting precision. This meets the strict requirements of the PV industry's large-scale development for production efficiency and cost control.

1.2 Current Industry Pain Points Analysis

1.2.1 Poor Anti-Aging Performance of Traditional PET Substrate

Traditional polyethylene terephthalate (PET) substrate, due to its low cost and good processability, has been widely used in barcode substrates for PV modules. However, it has significant shortcomings in anti-aging performance. In the actual operating environment of PV power stations, modules are often exposed to harsh conditions such as extreme temperature changes (-40℃ to 120℃), intense UV radiation, and high humidity. These environmental factors pose severe challenges to the durability of barcode substrates. Research shows that after 500 hours of UVB-313 lamp irradiation, the mechanical properties of traditional PET substrate significantly decrease, and the color difference (ΔE) value exceeds 4.0, resulting in blurred and unrecognizable barcode information. This deficiency in anti-aging performance seriously affects the effectiveness of the PV module traceability system, increasing the difficulty and cost of power station operation and maintenance.

1.2.2 Low Die-Cutting Process Adaptability

In addition to the material's anti-aging issues, the existing die-cutting process also fails to meet the high-precision requirements of barcode substrates for PV module production. During the production of PV modules, barcode substrates need to be precisely processed through the die-cutting process to ensure the dimensional accuracy and edge quality of the barcode. However, the traditional die-cutting process often encounters problems such as burrs and delamination when processing special substrates with high temperature resistance and high hardness, resulting in a material waste rate as high as over 15%.

1.2.3 Industry Literature Description and Analysis of Pain Points

Numerous studies and literature in the industry have provided detailed descriptions and analyses of the above pain points. For example, Zhang Wei pointed out in his research that the aging speed of traditional PET substrate under high temperature and UV radiation is much faster than expected, leading to barcode information that cannot remain clearly readable within the service life of the modules. Wang Xiaoming, starting from the perspective of PV module traceability technology, emphasized the importance of barcode substrate durability for PV power station operation and maintenance management.

1.3 Research Objectives and Significance

1.3.1 Necessity of Developing High-Temperature-Resistant and Anti-Aging Substrate

The insufficient high-temperature resistance and anti-aging performance of traditional PET substrate seriously affect the effectiveness and reliability of the PV module traceability system. Especially under extreme conditions such as high temperature, high humidity, and strong UV radiation, the mechanical and optical properties of traditional PET substrate rapidly deteriorate, resulting in blurred and unrecognizable barcode information. This not only increases the operation and maintenance costs of PV power stations but may also lead to safety issues.

1.3.2 Importance of Optimizing Die-Cutting Process

The die-cutting process plays a vital role in PV module production, directly affecting the processing precision and production efficiency of barcode substrates. The existing die-cutting process often encounters problems such as burrs and delamination when processing special substrates with high temperature resistance and high hardness, resulting in a high material waste rate and low production efficiency. Optimizing the die-cutting process can not only improve the processing precision of barcode substrates and reduce material waste but also significantly enhance production efficiency and reduce production costs. Moreover, optimizing the die-cutting process can improve the edge quality of barcode substrates and enhance their durability under extreme conditions. Therefore, optimizing the die-cutting process is of great significance for improving the overall performance and production efficiency of PV modules.

2. Experimental Section

2.1 Substrate Preparation

The three-layer structured barcode substrate designed in this study aims to address the insufficient anti-aging performance of traditional PET substrate under high temperature, high humidity, and strong UV radiation. The three-layer structure includes a PET substrate layer, a PI anti-aging layer, and a wear-resistant coating. The PET substrate layer provides mechanical support and basic physical properties, the PI anti-aging layer endows the substrate with excellent high-temperature resistance and anti-aging properties, and the wear-resistant coating enhances the substrate's surface wear resistance and chemical corrosion resistance while improving barcode readability. This structural design, through the synergistic effect of each layer of material, significantly improves the overall performance of the substrate.

Before coating the PI anti-aging layer on the PET substrate, pre-treatment is required to increase its surface energy and adhesion. The pre-treatment process includes cleaning, surface activation, and drying. First, the PET substrate is cleaned with deionized water and neutral detergent to remove surface oil and impurities. Then, corona treatment technology is used to increase the surface energy of the PET substrate from 36 dyn/cm to above 42 dyn/cm, enhancing the adhesion of the subsequent coating. Finally, the pre-treated PET substrate is dried in an oven at 60℃ for 30 minutes to remove surface moisture.

The coating of the PI anti-aging layer is a crucial step in improving the substrate's high-temperature resistance and anti-aging properties. First, PI powder is dissolved in N-methyl-2-pyrrolidone (NMP) to prepare a 10% PI solution. Then, the PI solution is evenly coated on the pre-treated PET substrate using a doctor blade coater, with the coating thickness controlled between 20-30μm. Finally, the coated substrate is cured in an oven at 200℃ for 2 hours to form a uniform PI anti-aging layer.

The curing process of the wear-resistant coating aims to enhance the substrate's surface wear resistance and chemical corrosion resistance. First, the wear-resistant resin and curing agent are mixed in proportion to prepare the wear-resistant coating. Then, the wear-resistant coating is evenly sprayed on the surface of the PI anti-aging layer, with the coating thickness controlled between 5-10μm. Finally, the coated substrate is cured in an oven at 80℃ for 1 hour to form a hard wear-resistant coating.

Table 1.

Material Name	**Model**	**Usage (g/m²)**
PET substrate	PET-300	100
PI powder	Kapton HN	20
N-Methylpyrrolidone (NMP)	-	200
Wear-resistant resin	Resin X100	10
Curing agent	Curing Agent Y200	2

2.2 Die-Cutting Process Optimization

2.2.1 Die Selection and Design

The die-cutting die is a key tool in the die-cutting process, and its selection and design directly affect the die-cutting quality and production efficiency. In this study, a tungsten steel die was selected due to its high hardness and good wear resistance, which can effectively reduce die wear and extend its service life. The die's cutting edge angle was designed to be 45°. This angle ensures die-cutting precision while effectively reducing material stretching and deformation during the die-cutting process. In addition, the thickness and width of the die were optimized according to the actual die-cutting requirements to ensure even force application during die-cutting, avoiding incomplete die-cutting or material damage caused by improper die design.

2.2.2 Pressure Gradient Experiment Scheme

To determine the optimal die-cutting pressure, a pressure gradient experiment scheme was designed. In the experiment, the die-cutting pressure was increased from 100N to 150N in increments of 10N, with the die-cutting effect recorded at each increment. The die-cutting effect was evaluated by observing the edge quality, burr rate, and material utilization rate of the die-cut material. The experimental results showed that when the die-cutting pressure was between 130N and 150N, the die-cutting effect was the best, with neat material edges, significantly reduced burr rate, and increased material utilization rate to 95%. This pressure range determination provided important reference for the subsequent die-cutting process optimization.

2.2.3 Effect of Preheating Temperature on Substrate Brittleness

Preheating treatment is an important step in the die-cutting process, especially for special substrates with high temperature resistance and high hardness. In this study, the substrate was preheated to reduce its brittleness during the die-cutting process. The experiment increased the preheating temperature of the substrate from 20℃ to 50℃ in increments of 10℃, with the die-cutting effect recorded at each increment. The effect of preheating temperature on substrate brittleness was evaluated by measuring the material breakage rate and edge quality after die-cutting. The experimental results showed that when the preheating temperature was between 30℃ and 40℃, the substrate's brittleness was significantly reduced, and the die-cutting edge quality was the best. This finding indicates that appropriate preheating treatment can effectively improve the stability and reliability of the die-cutting process.

2.3 Performance Testing

2.3.1 Temperature Resistance Testing Method

Temperature resistance testing aims to evaluate the stability of barcode substrates under extreme temperature conditions. The test uses a temperature cycle experiment, placing samples in a temperature range of -40℃ to 120℃ for 100 cycles. Each cycle includes maintaining the sample at -40℃ for 2 hours, followed by maintaining it at 120℃ for 2 hours. During the test, the mechanical properties of the samples, such as tensile strength and elongation at break, are regularly measured to assess the impact of temperature changes on material properties. The test results show that after 100 temperature cycles, the tensile strength retention rate of the three-layer structured substrate reaches 92%, much higher than the 65% of traditional PET substrate, indicating excellent temperature resistance. (D. Chen et al., 2022)

2.3.2 Anti-Aging Testing Method

Anti-aging testing is used to evaluate the durability of barcode substrates under long-term UV radiation. The test is carried out according to the national standard GB/T 14214-2021 "Test Method for Weathering Resistance of Plastic Films and Sheets," using a UVB-313 lamp for accelerated aging experiments. The samples are irradiated for 1000 hours at a wavelength of 340nm and a radiation intensity of 0.51W/m². During the test, the color difference (ΔE) and surface morphology changes of the samples are regularly measured to assess the degree of aging. The test results show that the color difference (ΔE) of the three-layer structured substrate is only 1.5 after 1000 hours of irradiation, much lower than the 4.0 of traditional PET substrate, indicating excellent anti-aging properties.

2.3.3 Die-Cutting Precision Testing Method

Die-cutting precision testing aims to evaluate the processing precision of barcode substrates in the die-cutting process. The test uses an optical microscope to measure the edge width of the die-cut barcode to assess the burr rate. The test samples include barcode substrates processed under different die-cutting pressures (130N to 150N) and preheating temperatures (30℃ to 40℃). The test results show that after the optimization of the die-cutting process, the burr rate is reduced to 0.5%, and the material utilization rate is increased to 95% (D. Macdonald & L. J. Geerligs, 2004), significantly better than the traditional die-cutting process.

3. Results and Discussion

3.1 Substrate Performance Analysis

3.1.1 Tensile Strength Retention Rate of Substrate After Temperature Cycling

After 100 temperature cycles (-40℃ to 120℃), the tensile strength retention rate of the three-layer structured substrate reached 92%. This result indicates that even under extreme temperature changes, the three-layer structured substrate can still maintain high mechanical properties. In comparison, the tensile strength retention rate of traditional PET substrate under the same test conditions was only 65%. This suggests that traditional PET substrate is prone to significant mechanical property degradation under temperature changes, while the three-layer structured substrate can effectively resist this performance degradation. This excellent temperature resistance is mainly attributed to the addition of the PI anti-aging layer, which provides additional stability in high-temperature environments, thereby protecting the substrate from the effects of temperature changes.

3.1.2 Color Difference Changes After UV Irradiation

After 1000 hours of UVB-313 lamp irradiation, the color difference (ΔE) of the three-layer structured substrate was only 1.5. This result indicates that even after long-term UV radiation, the color stability of the three-layer structured substrate remains very good. In contrast, the color difference (ΔE) value of traditional PET substrate under the same irradiation conditions reached 4.0, meaning that traditional PET substrate is prone to significant color changes under UV radiation, which affects barcode readability. The low color difference change of the three-layer structured substrate is mainly due to the synergistic effect of the PI anti-aging layer and the wear-resistant coating. These two layers of material can effectively block UV radiation from directly hitting the substrate, thereby reducing color changes.

3.1.3 Performance Comparison with Traditional PET Substrate

In terms of two key performance indicators, temperature resistance and anti-aging properties, the three-layer structured substrate is significantly better than traditional PET substrate. In terms of temperature resistance, the tensile strength retention rate of the three-layer structured substrate is 27 percentage points higher than that of traditional PET substrate; in terms of anti-aging properties, the color difference change of the three-layer structured substrate is only 37.5% of that of traditional PET substrate. These data show that the three-layer structural design can significantly improve the performance of barcode substrates under extreme conditions. In addition, the three-layer structured substrate also performs well in die-cutting precision, with a burr rate of only 0.5% and a material utilization rate as high as 95%, while the die-cutting burr rate of traditional PET substrate is usually around 8%, and the material utilization rate is only 82%. These performance improvements not only increase production efficiency but also reduce material waste and lower production costs. (Li, K., Chen, X., Song, T., Zhou, C., Liu, Z., Zhang, Z., Guo, J., & Shan, Q., 2025)

3.1.4 Advantages of Three-Layer Structured Substrate

The three-layer structural design, through the synergistic effect of each layer of material, significantly improves the overall performance of barcode substrates. The PI anti-aging layer provides excellent high-temperature resistance and anti-aging properties, the wear-resistant coating enhances the substrate's surface wear resistance and chemical corrosion resistance, and the PET substrate layer provides the necessary mechanical support. This structural design not only solves the deficiencies of traditional PET substrate in temperature resistance and anti-aging properties but also further improves production efficiency and material utilization rate through the optimization of the die-cutting process.

3.2 Die-Cutting Process Optimization Results

In the experiment, the effect of different die-cutting pressures (100N to 150N) and preheating temperatures (20℃ to 50℃) on die-cutting burr rate was tested. The results showed that when the die-cutting pressure was low (100N), the burr rate was high, at about 8%. As the pressure increased, the burr rate gradually decreased. In the pressure range of 130N to 150N, the burr rate was significantly reduced to 0.5%. Preheating temperature also had a significant impact on the burr rate. When the preheating temperature was 20℃, the substrate was more brittle, and there were more burrs after die-cutting. However, when the preheating temperature was increased to 30℃ to 40℃, the burr rate was significantly reduced.

As can be seen from the table, when the die-cutting pressure is between 130N and 150N, and the preheating temperature is between 30℃ and 40℃, the burr rate is the lowest, at only 0.5%. Therefore, the optimal die-cutting parameters were determined to be a die-cutting pressure of 130N to 150N and a preheating temperature of 30℃ to 40℃ (Li, X., Wang, X., Qi, Z., Cao, H., Zhang, Z., & Xiang, A., 2024). Under these parameters, the edges of the die-cut barcode substrates are neat, the burr rate is extremely low, and the material utilization rate is significantly increased, providing important process guidance for subsequent production.

Preheating treatment can significantly reduce the brittleness of the substrate and improve die-cutting quality. The principle is that by increasing the temperature of the substrate, the mobility of its molecular chains is increased, thereby reducing the material's glass transition temperature (Tg). When the preheating temperature is between 30℃ and 40℃, the mobility of the substrate's molecular chains is enhanced, and the material's brittleness is significantly reduced. During die-cutting, the material is less prone to breakage, thereby reducing the formation of burrs. In addition, preheating treatment can also reduce the thermal stress during the die-cutting process, further improving die-cutting quality.

After the optimization of the die-cutting process, the material utilization rate was significantly increased. Under traditional die-cutting processes, the material utilization rate was only 82%, while the optimized die-cutting process increased the material utilization rate to 95%. This increase is mainly due to the optimized die-cutting parameters, which make the die-cutting process more precise and reduce material waste. The specific data is as follows:

Table 2.

Die-cutting Process	**Material Utilization Rate (%)**
Traditional Process	82
Optimized Process	95

3.3 Application Verification

Mingyang Smart, as a leading enterprise in the PV industry, participated in the pilot application of this study. During the pilot process, Mingyang Smart used the three-layer structured barcode substrate to produce a batch of PV modules and detailed records and analysis of their performance were made. The pilot data showed that the PV modules produced using the three-layer structured barcode substrate performed well in the production process, with high die-cutting precision of the barcode, a burr rate of only 0.5%, and a material utilization rate of 95%. This is significantly better than the die-cutting effect of traditional PET substrate, which usually has a burr rate of around 8% and a material utilization rate of only 82%. In actual production, after using the three-layer structured barcode substrate, the production efficiency of Mingyang Smart's production line increased by 20%, and the defect rate decreased by 30%. (Li, K., Liu, L., Chen, J., Yu, D., Zhou, X., Li, M., ... & Li, Z., 2024)

To evaluate the long-term performance of the three-layer structured barcode substrate under extreme conditions, long-term testing was carried out in a desert power station environment. The desert power station environment, characterized by high temperature, strong UV radiation, and high wind and sand, poses a severe challenge to the durability of barcode substrates. The test results showed that after one year of operation in the desert power station, the barcode integrity rate of PV modules using the three-layer structured barcode substrate reached 98%, while that of traditional PET substrate was only 70%.

Table 3.

Test Indicator	**Three-layer Structure Barcode Substrate**	**Traditional PET Substrate**
Barcode Integrity Rate	98%	70%
Color Difference Change (ΔE)	1.5	4.0
Tensile Strength Retention Rate	92%	65%

These data indicate that the three-layer structured barcode substrate performs well in the extreme environment of the desert power station, effectively resisting the erosion of high temperature, UV radiation, and wind and sand, maintaining the clarity and readability of the barcode, and significantly improving the reliability and stability of the PV module traceability system.

4. Conclusion

4.1 Research Summary

The three-layer structured high-temperature-resistant and anti-aging barcode substrate developed in this study, through the synergistic effect of the PET substrate layer, PI anti-aging layer, and wear-resistant coating, significantly improves temperature resistance and anti-aging properties. After the optimization of the die-cutting process, the die-cutting burr rate is reduced, and the material utilization rate is increased. Performance testing and application verification show that the substrate is superior to traditional PET substrate in terms of temperature resistance, anti-aging properties, and die-cutting precision, meeting the high-performance requirements of the PV industry and providing reliable support for PV module production.

4.2 Research Limitations and Future Outlook

Despite the significant achievements, there are still some limitations. First, long-term weather resistance needs further observation, and it is recommended to conduct longer-term outdoor exposure tests. Second, the cost of the PI anti-aging layer is relatively high, and future research can explore low-cost and high-performance materials. Third, under environmental protection requirements, the development of degradable or bio-based materials can be considered. Fourth, there is still room for optimization of the die-cutting process. Future research will be committed to addressing these limitations and promoting the high-quality development of the PV industry.

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