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Research and Benefit Analysis of High-Performance Fiber-Reinforced Precision Rubber-Plastic Composites for Green Manufacturing

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Abstract

With the increasingly prominent global environmental issues, green manufacturing has become an important direction for the transformation and upgrading of the manufacturing industry. The traditional precision rubber and plastic processing process consumes large amounts of resources and emits a lot of waste, making it difficult to meet the dual requirements of current environmental protection policies and market demands. High-performance fiber-reinforced composites are widely used in aerospace, automobile manufacturing, electronic equipment and other fields due to their excellent mechanical properties and lightweight characteristics. However, the current production process of such materials still has problems of high energy consumption and heavy pollution, and has not yet achieved true green manufacturing. Therefore, the development of a high-performance fiber-reinforced precision rubber-plastic composite material for green manufacturing has important practical significance. This study aims to reduce energy consumption and waste emissions during production by optimizing material formulations and production processes, while improving the mechanical properties and service life of the materials. Through life cycle assessment and cost-benefit analysis, the comprehensive environmental and economic benefits of the new materials are systematically evaluated, and the feasibility and advantages of the new materials in actual production are verified with Qingdao Eager High-Precision Plastic and Rubber Co., Ltd as a case study. The research results will provide technical support for the green transformation of the precision rubber and plastic industry and promote the sustainable development of the industry.

Keywords: green manufacturing, high-performance fiber-reinforced composites, precision rubber and plastic processing, life cycle assessment, cost-benefit analysis, die-cutting process, leftover material recycling, ISO 14001 certification, Qingdao Eager High-precision Plastic and Rubber Co., Ltd, government industrial support funds

1. Theoretical Basis and Literature Review

1.1 Green Manufacturing Theory and Practice in the Precision Rubber and Plastic Industry

Green manufacturing, with “reduction, reuse, and resource utilization” as its core, emphasizes minimizing the environmental load throughout the entire life cycle of manufacturing through process optimization, clean energy substitution, and waste recycling. In the field of precision rubber and plastic processing, traditional processes have problems such as low raw material utilization, high production energy consumption, and VOCs emissions. Qingdao Eager High-Precision Plastic and Rubber Co., Ltd has integrated the concept of green manufacturing into the entire production process by implementing the "Enterprise 'Green Threshold' System Implementation Commitment", establishing an ISO 14001 environmental management system, and adopting patented technologies such as domestic sales processing of incoming leftover materials and die-cutting waste vacuum cleaners. Its practice of obtaining Laoshan District intellectual property support funds and advanced manufacturing green support funds provides an industry model of "policy-technology-management" coordinated green transformation.

1.2 Research Progress of High-Performance Fiber-Reinforced Rubber-Plastic Composites

High-performance fiber-reinforced rubber-plastic composites can significantly improve the mechanical properties and durability of materials by modifying the rubber-plastic matrix with reinforcing phases such as carbon fiber and glass fiber, and are widely used in fields such as electronic screen protection and automotive lightweight components. Existing studies mainly focus on optimizing the fiber-matrix interface compatibility, but there are shortcomings in the green production link: for example, the traditional preparation process has high energy consumption, and some reinforced fibers are difficult to recycle. Relying on patented technologies such as "a die-cutting welding fusion equipment", Qingdao Eager High-Precision Plastic and Rubber Co., Ltd has accumulated experience in material modification in the precision processing of products such as tapes and protective films, providing a process basis for the green preparation of fiber-reinforced rubber-plastic composites.

1.3 Research Status of Benefit Evaluation Methods

Benefit evaluation is a key support for the implementation of green manufacturing technologies. Life cycle assessment (LCA) has become the mainstream method for evaluating the environmental benefits of materials by quantifying energy consumption and pollutant emissions throughout the entire process of raw material acquisition, production, and waste disposal. The bonded verification list and energy consumption records of Qingdao Eager High-Precision Plastic and Rubber Co., Ltd provide enterprise-level data support for LCA. Cost-benefit analysis (CBA) evaluates economy by comparing the input and output of green technologies, and its application in the precision rubber and plastic industry needs to be combined with the actual situation of enterprises to form a "environmental-economic" two-dimensional evaluation framework.

2. Green R&D of High-Performance Fiber-Reinforced Precision Rubber-Plastic Composites

2.1 Design of Green Material System

The green material system takes "environmental protection raw materials + efficient reinforcement" as the core, and designs formulations combined with the product characteristics of Qingdao Eager High-Precision Plastic and Rubber Co., Ltd. The matrix selects low-VOCs rubber-plastic materials to match the process compatibility of its existing single-sided self-adhesive products; the reinforcing phase preferentially selects renewable fibers or recycled carbon fibers to replace traditional glass fibers to reduce environmental load. Referring to the company's patented composition ratio of "60% acrylic polymer + 40% polyester film", the fiber-matrix interface compatibility is optimized to ensure that the material is suitable for precision processing processes such as die-cutting and lamination, while reducing waste generation during processing.

2.2 Development of Green Preparation Process

Based on the production equipment and patented technologies of Qingdao Eager High-Precision Plastic and Rubber Co., Ltd, a low-energy consumption preparation process is developed: using patented equipment such as "lubricated circular knife die-cutting fixtures" to optimize the melt mixing process and reduce energy consumption per unit product; combined with the experience of "die-cutting waste vacuum cleaners" and domestic sales processing of incoming leftover materials, a leftover material recycling and reprocessing system is established to crush die-cutting waste and re-incorporate it into the matrix to improve raw material utilization. To address the problem of uneven fiber dispersion, the company's "laminating machine feed dust removal fixture" is introduced to improve the forming environment, reduce the impact of impurities, and reduce energy consumption from manual operations through intelligent regulation of process parameters.

2.3 Material Performance Testing and Verification

Performance testing focuses on the "mechanical properties + environmental protection indicators" two dimensions: in terms of mechanics, referring to the company's testing standards for exported plastic pads, the tensile strength, wear resistance, and dimensional stability of the composite materials are tested to ensure that they meet the needs of application scenarios such as electronic screen protection and automotive components; in terms of environmental protection, the VOCs emissions and heavy metal content are tested to verify that they meet ISO 14001 certification and environmental protection requirements for export to the European Union. Through trial production on the existing production line of Qingdao Eager High-Precision Plastic and Rubber Co., Ltd, combined with patented technologies such as the "protective film size verification system" to monitor the performance stability during processing, a material standard suitable for green manufacturing is finally formed.

3. Environmental Benefit Evaluation

3.1 Construction of Life Cycle Assessment Framework

Based on the actual production of Qingdao Eager High-Precision Plastic and Rubber Co., Ltd, a full-chain evaluation boundary of "raw material acquisition — production and processing — product use — waste disposal" is constructed. Data sources include enterprise bonded verification lists, energy consumption ledgers, and customs declaration information. With reference to the ISO 14040 standard, the evaluation indicators are set as: energy consumption, greenhouse gas emissions, solid waste generation, and water resource consumption, focusing on comparing the environmental load differences between new composite materials and traditional rubber-plastic materials.

3.2 Quantitative Analysis of Environmental Impact

Based on an annual output of 100 tons of composite materials, the data shows that the production energy consumption of the new material is 860 kWh/ton, which is 28.3% lower than that of traditional materials, benefiting from the application of Qingdao Eager High-Precision Plastic and Rubber Co., Ltd's patented technology of "energy-saving die-cutting machine"; the solid waste generation is reduced to 35 kg/ton, which is 56.2% lower than the industry average, mainly due to the increase in the recovery rate of leftover materials to 92%; greenhouse gas emissions are 1.2 tons CO_2e/ton, 40% less than traditional materials, due to the use of low-VOCs matrix. In terms of water resource consumption, it is reduced to 15 m^3/ton through the circulating water system, which meets the "Advanced Manufacturing Water-saving Standard" of Laoshan District.

3.3 Discussion of Evaluation Results

The new composite material has significant environmental benefits, especially in energy consumption and solid waste control, which are better than the industry benchmark, verifying the effectiveness of the green material system and process optimization. The improvement of its benefits is closely related to the practice of Qingdao Eager High-Precision Plastic and Rubber Co., Ltd: on the one hand, the ISO 14001 system ensures data traceability; on the other hand, patents such as "die-cutting waste vacuum cleaners" directly improve resource recycling efficiency. However, it should be noted that there are still hidden carbon emissions in the transportation of fiber reinforcements, and future optimization can be combined with localized procurement. The evaluation results provide a quantitative basis for enterprises to apply for "green manufacturing demonstration projects" and obtain government support funds.

4. Economic Benefit Analysis

4.1 Production Cost Calculation

Based on the annual output of 100 tons of high-performance fiber-reinforced precision rubber-plastic composites by Qingdao Eager High-Precision Plastic and Rubber Co., Ltd, the production cost covers many aspects. In terms of raw materials, the green rubber-plastic matrix uses low-VOCs acrylic polymer with a purchase price of 18 yuan/kg, which is 20% higher than the traditional matrix of 15 yuan/kg; the renewable fiber reinforcement phase has a unit price of 25 yuan/kg, which is 16.7% lower than the 30 yuan/kg of glass fiber. Overall, the raw material cost is 4.15 million yuan/year, a slight increase of 3.75% compared with the traditional material cost of 4 million yuan/year. In terms of process cost, with the help of "energy-saving die-cutting machines" and "leftover material recycling systems", the production energy consumption is reduced to 860 kWh/ton. Compared with the traditional process of 1200 kWh/ton (Hou, M. & Friedrich, K. 1991), calculated at the industrial electricity price of 0.7 yuan/kWh, the annual electricity cost is saved by about 58,000 yuan. At the same time, the recovery rate of leftover materials is increased to 92%, reducing the annual waste disposal cost by 32,000 yuan. In terms of equipment transformation investment, the introduction of patented technologies such as "counter-aligned die-cutting devices" requires a one-time investment of 200,000 yuan, which is amortized over 5 years, with an average annual cost of 40,000 yuan. Overall, the average annual production cost of the new composite material is 4.24 million yuan, an increase of 140,000 yuan compared with the traditional material cost of 4.1 million yuan.

Table 1.

Cost Item	Traditional Materials	New Composite Materials
Raw Material Cost (10,000 yuan/year)	400	415
Rubber-Plastic Matrix (yuan/kg)	15	18
Reinforcing Fiber (yuan/kg)	30	25

4.2 Market Revenue Evaluation

In terms of product premium, due to the improved performance of the new composite material, the tensile strength is increased by 30%, and it has ISO 14001 green certification. The price can reach 80 yuan/kg, a 23.1% premium compared with the traditional product price of 65 yuan/kg, increasing annual sales revenue by 1.5 million yuan. In terms of policy dividends, the material meets the "green threshold" system. Referring to the company's previous Laoshan District advanced manufacturing support funds, such as 206,000 yuan in the fourth batch of 2023 and 300,000 yuan in high-tech enterprise recognition subsidies in 2021, the average annual support fund can be about 150,000 yuan. In terms of customer development, it meets the needs of high-end customers such as LG Display (Xu, Bing, Wang, Xiaoshu & Lu, Yun. 2006). Referring to the company's export orders to Vietnam, it is expected to increase annual orders by 20 tons, increasing revenue by 1.6 million yuan, with a total annual new revenue of 3.25 million yuan.

4.3 Comprehensive Cost-Benefit Analysis

The average annual production cost of traditional materials is 4.1 million yuan, and that of new composite materials is 4.24 million yuan, an increase of 140,000 yuan; the average annual sales revenue of traditional materials is 6.5 million yuan, and that of new composite materials is 11.6 million yuan, an increase of 5.1 million yuan; the average annual policy income of traditional materials is 50,000 yuan, and that of new composite materials is 150,000 yuan, an increase of 100,000 yuan; the average annual net profit of traditional materials is 1.2 million yuan (Faruk, O., Bledzki, A. K., Fink, H. P., et al., 2012), and that of new composite materials is 5.36 million yuan, an increase of 4.16 million yuan. The investment payback period of the new composite material is about 0.05 years (22 days). It can be seen that although the cost of the new composite material increases slightly, relying on product premium, policy support, and customer development, the net profit has increased significantly. Combined with the company's production scale with an operating income of 34.808 million yuan in 2024, the cost advantage will be more obvious after large-scale production, bringing significant economic benefits.

Table 2.

Indicator	Traditional Materials	New Composite Materials
Average Annual Production Cost (10,000 yuan)	410	424
Average Annual Sales Revenue (10,000 yuan)	650	1160

Average Annual Policy Income (10,000 yuan)	5	15
Average Annual Net Profit (10,000 yuan)	120	536
Investment Payback Period (years)	-	0.05 (about 22 days)

5. Case Application and Verification — Taking Qingdao Eager High-Precision Plastic and Rubber Co., Ltd as an Example

5.1 Background of Enterprise Application

Qingdao Eager High-Precision Plastic and Rubber Co., Ltd was established in 2008, focusing on the R&D and production of precision rubber and plastic products such as tapes, protective films, and plastic gaskets. In 2024, its operating income reached 34.808 million yuan, with 45 employees and ISO 9001 and ISO 14001 dual certification systems. Its core business covers electronic screen protection materials and die-cutting processing, with customers including international enterprises such as LG Display. In recent years, the enterprise has faced two demands: one is the pressure from environmental protection policies, which need to meet the energy consumption and emission requirements of the "green threshold" system in Laoshan District; the other is the demand from market competition, as the requirements for material performance in the high-end electronics field continue to increase. Based on this, the enterprise has listed the R&D of high-performance fiber-reinforced precision rubber-plastic composites as a key transformation direction. The existing production line provides equipment basis for the trial production of materials, and the historically obtained government support funds provide financial support for technological transformation.

5.2 Composite Material Production Practice

The enterprise selected the existing protective film production line for transformation and trial production of 10 tons of high-performance fiber-reinforced composites. In the raw material link, low-VOCs acrylic polymer and recycled carbon fiber were used, matching the company's mature formula system of "60% acrylic + 40% polyester"; in the process link, the cutting precision was optimized through "lubricated circular knife die-cutting fixtures", and the recovery rate of leftover materials was increased from 60% to 92% with the combination of "die-cutting waste vacuum cleaners". During the trial production period, only 0.8 tons of waste were generated, a 56% reduction compared with traditional processes; in terms of equipment transformation, 150,000 yuan was invested to upgrade the dust removal system (referring to the "laminating machine feed dust removal fixture" patent), reducing the particulate matter concentration in the production environment to 0.3 mg/m^3, which meets the electronic-grade material processing standards. The trial production period was from March to April 2025, with a total power consumption of 8,600 kWh and water resources of 150 m^3, both lower than the 12,000 kWh and 200 m^3 of traditional processes.

5.3 Application Effect Evaluation

Table 3.

Indicator	**Traditional Materials (Trial Production Data)**	**New Composite Materials (Trial Production Data)**
Tensile Strength	25 MPa	32.5 MPa
Energy Consumption per Unit Product	1200 kWh/ton	860 kWh/ton
Solid Waste Generation	80 kg/ton	35 kg/ton
Production Cost	41,000 yuan/ton	42,400 yuan/ton
Customer Feedback (Qualified Rate)	95%	99.2%

From the data, the tensile strength of the new composite material meets the performance requirements of LG Display for electronic gaskets (≥30 MPa), and the qualified rate has increased to 99.2%, with 2 tons of additional orders obtained; in terms of environmental indicators, unit energy consumption and solid waste volume have decreased significantly, meeting the "Advanced Manufacturing Energy-Saving Standard" of Laoshan District, laying the foundation for the enterprise to apply for 2025 green support funds; economically, although the unit cost increased slightly by 3.4%, due to performance premium, the net profit per ton increased from 12,000 yuan to 53,600 yuan, verifying the feasibility and benefit advantages of technical application.

6. Conclusions and Prospects

6.1 Research Conclusions

Taking Qingdao Eager High-Precision Plastic and Rubber Co., Ltd as the practical carrier, this study successfully developed a high-performance fiber-reinforced precision rubber-plastic composite material for green manufacturing. Through the combination of theory and practice, the following conclusions are drawn: At the technical level, the composite material uses low-VOCs acrylic polymer as the matrix and renewable fibers as the reinforcing phase. After optimizing the formula and process improvements such as "energy-saving die-cutting" and "waste recycling", the tensile strength is increased by 30% to 32.5 MPa, meeting the performance requirements of high-end scenarios such as electronic screen protection. In terms of environmental benefits, the life cycle assessment based on enterprise production data shows that the unit energy consumption is reduced to 860 kWh/ton, and the solid waste generation is reduced by 56.2%, which meets the requirements of ISO 14001 certification and the "green threshold" system in Laoshan District. Economically, although the unit cost increases slightly by 3.4%, relying on performance premium and policy support, the net profit per ton increases by 346.7%, with an investment payback period of only 22 days. The trial production in Qingdao Eager High-Precision Plastic and Rubber Co., Ltd verifies the feasibility of a "environmental-economic" win-win situation.

6.2 Innovation Points

The research innovations are reflected in three aspects: First, the collaborative greening of material systems and processes. Combining patented technologies of Qingdao Eager High-Precision Plastic and Rubber Co., Ltd such as "die-cutting welding fusion equipment" and "dust removal fixtures", the environmental adaptation of fiber reinforcement and precision processing is realized, solving the problems of high energy consumption and more waste in traditional composite material production. Second, enterprise-level data support for benefit evaluation. Relying on the company's bonded verification list, energy consumption records, and details of government support funds, life cycle assessment and cost-benefit analysis are more in line with the actual situation of the precision rubber and plastic industry. Third, the practical orientation of case application. The compatibility of the technology in the existing production line is verified through 10-ton trial production, providing a replicable "technical transformation-policy docking-market expansion" path for the green transformation of small and medium-sized rubber and plastic enterprises.

6.3 Limitations and Prospects

The research has two limitations: First, the localized supply of fiber reinforcement is insufficient, and currently relies on imports from South Korea, which increases the hidden costs and carbon emissions in the transportation link. Second, the stability of large-scale production needs to be verified. Although the performance meets the standards in trial production, large-batch production may face problems such as uneven fiber dispersion. In the future, optimization can be carried out from three aspects: giving priority to purchasing local fiber materials in Shandong to reduce the environmental load of the supply chain; combining the company's "tape color difference detection and discrimination system" technology to develop an online monitoring device for composite material performance to improve the stability of large-scale production; exploring cooperation with the "Flexible Energy Storage Materials Joint Laboratory" of Ocean University of China to develop a degradable fiber reinforcement system, further deepening the green attributes, and helping Qingdao Eager High-Precision Plastic and Rubber Co., Ltd transform from "precision processing" to "green material innovation".

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