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The Influence of Surface Treatment of Mold Materials on the Service Life of Low-Voltage Electrical Component Molds and Green Manufacturing Strategies

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Abstract: This article examines the influence of mold material surface treatments on the service life of molds used for low-voltage electrical components, with an emphasis on green manufacturing strategies. The properties of commonly used mold materials are analyzed, and advanced surface treatment technologies, such as physical vapor deposition (PVD) coatings, are introduced. The relationship between microstructural characteristics and service performance is investigated, along with the effects of surface treatments on tribological behavior and failure mechanisms. In addition, green manufacturing approaches, including low-temperature plasma treatment process optimization and chromium-free passivation technologies, are discussed. The study highlights the critical role of intelligent technologies in advancing sustainable mold manufacturing and outlines future development directions.

Keywords: Low-voltage electrical accessories mold; Surface treatment technology; Green manufacturing

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1. Introduction

The 14th Five-Year Plan for Industrial Green Development promulgated in 2021 explicitly proposes promoting the green transformation of the manufacturing industry. Against this policy background, research on the impact of mold material surface treatment on the lifespan of low-voltage electrical accessory molds and green manufacturing strategies is particularly important. Low-voltage electrical accessory molds commonly use carbon tool steel and alloy steel, with different materials exhibiting distinct characteristics. Surface treatment technologies such as PVD coating and plasma nitriding can enhance mold performance. Additionally, through metallographic analysis, hardness testing, and other methods, the correlation between microstructure and service performance can be explored, along with the influence of surface treatment on tribological properties and failure modes. Furthermore, green manufacturing strategies are developed in areas such as low-temperature plasma treatment, chromium-free passivation technology, and modular design, leveraging intelligent technologies to achieve adaptive adjustment of process parameters, collectively promoting the green development of low-voltage electrical accessory mold manufacturing.

2. Fundamentals of mold materials and surface treatment technologies

2.1. Classification and performance requirements of mold materials for low-voltage electrical accessories

Mold materials commonly used for low-voltage electrical accessories mainly include carbon tool steel and alloy steel. Carbon tool steel has a high carbon content, is relatively inexpensive, and possesses certain hardness and wear resistance, suitable for producing low-voltage electrical accessory molds with less stringent precision and lifespan requirements. However, its hardenability is poor, and quenching deformation is significant. Alloy steel, due to the addition of various alloying elements, offers superior comprehensive performance. The incorporation of alloy elements improves hardenability, tempering stability, and wear resistance, enabling it to adapt to more complex service environments and making it suitable for manufacturing high-precision, long-lifespan low-voltage electrical accessory molds. For instance, in molds subjected to large impact loads or requiring high dimensional stability, alloy steel performs excellently. Low-voltage electrical accessory mold materials must possess good mechanical properties, such as high strength, high hardness, and high wear resistance, to withstand pressure and friction during service, while also demonstrating good adaptability to service environments, ensuring stable operation under varying working conditions [1].

2.2. Current development status of surface treatment technologies

Surface treatment technologies in the mold industry are continuously innovating and developing. Currently, PVD coating technology is increasingly favored in low-voltage electrical accessory mold manufacturing due to its ability to form thin films with high hardness, good wear resistance, and low friction coefficients on mold surfaces. It effectively improves mold surface quality and performance, reducing wear and corrosion while extending mold lifespan. Plasma nitriding technology is also widely applied, forming a nitrogen-rich hardened layer on the mold surface that significantly enhances hardness, wear resistance, and anti-seizing properties. These two mainstream surface strengthening technologies play a key role in the mold industry's progression toward high precision, long lifespan, and high performance, with their application trends continuously expanding and deepening, providing strong support for efficient and high-quality manufacturing of low-voltage electrical accessory molds [2].

3. Mechanisms of surface treatment impact on mold lifespan

3.1. Correlation between microstructure and service performance

Through metallographic analysis and hardness testing, the close correlation between microstructure and mold service performance can be deeply revealed. Different thicknesses of surface modification layers significantly affect the mold's resistance to plastic deformation. Thicker modification layers often provide stronger support, reducing the likelihood of plastic deformation under harsh service conditions such as high pressure and high speed [3]. Phase composition is equally critical, as different phases exhibit distinct mechanical properties; a rational phase composition can optimize overall mold performance. For example, the presence of certain strengthening phases can improve mold hardness and wear resistance, thereby extending lifespan. This correlation between microstructure and service performance essentially reflects the reshaping of the mold's internal structure by surface treatment, altering its ability to resist external loads and ultimately profoundly influencing mold lifespan.

3.2. Tribological performance and failure mode analysis

Surface treatment of mold materials significantly affects tribological performance and failure modes, thereby determining mold lifespan. Surface roughness is a key factor; rough surfaces easily lead to stress concentration, exacerbating friction and wear during operation of low-voltage electrical accessory molds and reducing lifespan. After appropriate surface treatment reduces roughness, the friction coefficient decreases, and wear slows. Coating adhesion is also important, where insufficient adhesion causes coatings to peel off during mold operation, failing to effectively protect the mold surface and accelerating failure. Through friction and wear experiments, a quantitative relationship model between surface roughness, coating adhesion, and mold wear lifespan can be established [4]. This model precisely reveals their internal connections, aiding in-depth understanding of the mechanisms by which surface treatment affects mold lifespan, providing theoretical basis for optimizing surface treatment processes and extending mold lifespan, enabling low-voltage electrical accessory molds to achieve efficient, long-lifespan operation under the green manufacturing concept.

4. Construction of green manufacturing strategy system

4.1. Development of environmentally friendly surface treatment technologies

4.1.1. Optimization of low-temperature plasma treatment process

In optimizing low-temperature plasma treatment processes, focus is placed on studying the effects of process parameters on treatment efficiency and environmental impact factors [5]. Specifically, in-depth exploration of how changes in parameters such as plasma power, treatment time, and gas flow affect treatment efficiency. Higher plasma power may accelerate the process but could increase energy consumption and equipment wear; excessively long treatment times may improve effects but reduce production efficiency. Meanwhile, these parameter changes also influence environmental impact factors, such as improper gas flow potentially increasing harmful gas emissions. Based on this, a balance model between energy consumption and performance is constructed. Through this model, process parameters are precisely regulated while ensuring mold surface treatment quality and performance, minimizing energy consumption and achieving green manufacturing goals, effectively extending the lifespan of low-voltage electrical accessory molds.

4.1.2. Research on chromium-free passivation technology

In green manufacturing strategies for mold material surface treatment, research on chromium-free passivation technology is of great significance. Traditional chromate passivation processes effectively protect molds but involve chromium, a heavy metal that causes severe environmental pollution, conflicting with green manufacturing principles. Accordingly, developing new anti-corrosion coating systems based on silane modification becomes key. Silane, with its unique chemical structure, forms strong chemical bonds with mold surfaces while offering good film-forming properties and corrosion resistance. Studies show that silane-modified chromium-free passivation coatings can be prepared with excellent performance, not only avoiding heavy metal pollution but also forming dense protective films on mold surfaces, enhancing corrosion resistance and thereby extending the service life of low-voltage electrical accessory molds [6]. This new chromium-free passivation technology provides an important direction for the green development of mold material surface treatment.

4.2. Full-life-cycle green design methods

4.2.1. Modular detachable structure design

Modular detachable structure design is a key aspect of full-life-cycle green design methods. During the mold design stage, the mold is divided into different functional modules with standardized interfaces for easy disassembly and assembly [7]. This design effectively reduces maintenance difficulty; when a component is damaged, the corresponding module can be directly disassembled and replaced, avoiding large-scale repairs or replacement of the entire mold and significantly reducing material waste during maintenance. Additionally, detachable structures facilitate mold material recycling and reuse. At the end of mold lifespan, modules can be disassembled and recycled by material type, improving resource utilization. Moreover, modular design facilitates mold upgrades and optimizations, replacing specific modules achieves performance improvements without discarding the entire mold, practicing green manufacturing principles from multiple aspects and enhancing the sustainability of low-voltage electrical accessory molds.

4.2.2. Environmental impact assessment based on LCA

In constructing a green manufacturing strategy system for mold material surface treatment, environmental impact assessment based on LCA (Life Cycle Assessment) in full-life-cycle green design methods is particularly crucial. LCA systematically analyzes the entire mold process from raw material acquisition and processing to disposal and recycling [8]. By quantifying potential environmental impacts such as resource and energy consumption and pollutant emissions at each stage, key environmental load links are identified. For example, assessing ecological damage from mining in raw material acquisition; analyzing chemical use and energy consumption in surface treatment during processing; and considering recycling methods' environmental effects in disposal. This provides comprehensive and scientific environmental impact basis for formulating green manufacturing strategies for molds, aiding in balancing mold material surface treatment with environmental protection and enhancing the sustainable development capability of the mold industry.

5. Innovation paths for integration of intelligent technologies

5.1. Intelligent control of surface treatment processes

5.1.1. Adaptive adjustment system for process parameters

In mold material surface treatment, adaptive process parameter adjustment systems are crucial. Leveraging intelligent technology integration and innovation, this system automatically adjusts parameters based on real-time monitoring data. For example, sensors collect key parameter information such as mold surface temperature and pressure, which is transmitted to machine learning-based algorithm models [9]. The models deeply analyze the data, quickly determining if current parameters are optimal; if deviations occur, appropriate adjustments are rapidly calculated, precisely regulating coating equipment current, gas flow, and other parameters to maintain coating thickness in the ideal range. This not only effectively improves surface treatment quality and ensures low-voltage electrical accessory mold performance but also optimizes the process, increasing production efficiency, reducing resource waste, and laying a solid foundation for green manufacturing of mold material surface treatment.

5.1.2. Application of digital twin technology

In mold material surface treatment processes, digital twin technology plays a key role. By constructing virtual simulation models of surface treatment equipment, precise simulation and real-time monitoring of equipment operating states are achieved. These virtual models comprehensively reflect the characteristics and behavior of physical entities, covering structure, materials, process parameters, etc. [10]. Using these models, the impact of different parameters on surface treatment effects can be deeply analyzed, optimizing process scheme formulation. For instance, when treating low-voltage electrical accessory molds, parameters such as temperature, time, and treatment solution concentration can be precisely adjusted based on virtual simulation results, achieving optimal surface treatment, improving mold surface quality, enhancing wear and corrosion resistance, effectively extending mold lifespan, and realizing green manufacturing by reducing resource consumption and environmental pollution.

5.2. Intelligent mold health management

5.2.1. Multi-source information fusion monitoring technology

In intelligent mold health management, multi-source information fusion monitoring technology integrates stress sensors and image recognition systems as key components. Stress sensors precisely acquire real-time stress data during mold production, analyzing stress distribution and changes to detect internal structural pressure conditions and identify potential stress concentration areas, often hidden failure risks. Image recognition systems visually monitor mold surface wear, cracks, etc. Advanced image processing algorithms precisely identify subtle surface damage. Fusing stress sensor data with image recognition results establishes a comprehensive and accurate mold failure early warning mechanism. Through integrated analysis of multi-source information, timely and reliable mold failure prediction is achieved, providing a strong basis for advanced maintenance measures, effectively extending low-voltage electrical accessory mold lifespan while laying a solid foundation for green mold manufacturing.

5.2.2. Development of remaining life prediction algorithms

In intelligent mold health management, the remaining life prediction algorithm development achieves precise maintenance cycle prediction based on deep learning fatigue damage evolution modeling. By collecting extensive production data such as stress-strain and temperature changes, datasets related to mold fatigue damage are built. Leveraging deep learning’s powerful nonlinear mapping capabilities, these data are deeply mined to capture fatigue damage evolution patterns over time and usage cycles, establishing precise fatigue damage evolution models. These models not only reflect current damage states in real time but also predict future damage trends under set conditions, accurately forecasting remaining mold life and providing basis for scientific maintenance cycles, ensuring safe and reliable operation while avoiding resource waste from excessive maintenance, strongly supporting green manufacturing of low-voltage electrical accessory molds.

5.3. Green manufacturing decision support system

5.3.1. Construction of multi-objective optimization model

In research on the impact of mold material surface treatment on low-voltage electrical accessory mold lifespan and green manufacturing strategies, multi-objective optimization model construction is a key link. Multiple objectives, such as mold lifespan, production costs, and environmental impact must be comprehensively considered. On one hand, quantitative relationships between surface treatment process parameters and mold lifespan are analyzed, such as the impact of different coating processes on wear and corrosion resistance and thus lifespan, establishing lifespan prediction sub-models. On the other hand, ecological benefit indicators like resource consumption, energy use, and waste emissions for various processes are calculated, building ecological benefit assessment sub-models. Meanwhile, equipment, material, and labor costs for processes are considered, constructing economic cost assessment sub-models. Through reasonable weight allocation, these sub-models are fused into a comprehensive multi-objective optimization model, providing scientific decision basis for selecting optimal green manufacturing process schemes and aiding in balancing economic and ecological benefits in mold manufacturing.

5.3.2. Application of knowledge graph technology

In research on mold material surface treatment, low-voltage electrical accessory mold lifespan, and green manufacturing strategies, knowledge graph technology plays a key role. Knowledge graphs integrate multi-source heterogeneous data such as mold materials, surface treatment processes, and environmental standards, structurally presenting information on mold material characteristics, impacts of different surface treatment methods on mold lifespan, and green manufacturing-related environmental requirements in graph form. Through knowledge graphs, decision support systems achieve intelligent reasoning and querying, quickly and accurately providing technicians with mold material selection and surface treatment process optimization suggestions while ensuring compliance with environmental standards. Technicians can intuitively understand factor associations, such as lifespan improvement effects of specific surface treatments on certain mold materials and the advantages/disadvantages of those processes in green manufacturing, aiding scientific decisions and promoting green and efficient mold manufacturing.

6. Conclusion

Mold material surface treatment significantly impacts the lifespan of low-voltage electrical accessory molds. Different surface treatment technologies influence mold lifespan by altering surface microstructure and mechanical properties, acting on failure forms such as wear, corrosion, and fatigue, exhibiting certain patterns. The integration of green manufacturing concepts with intelligent technologies points to new directions for low-voltage electrical accessory mold manufacturing, with the key lying in incorporating intelligent means into all links of green manufacturing, such as intelligent production process control to reduce energy consumption and improve resource utilization. In the future, efforts should strengthen the development of environmentally friendly materials to reduce environmental impact from the source; meanwhile, focus on integrating intelligent sensing systems for real-time mold status monitoring, achieving precise maintenance and optimization, and promoting the development of low-voltage electrical accessory mold manufacturing toward greener, more efficient, and intelligent directions.

Disclosure statement

The author declares no conflict of interest.

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