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Research on Cost Control Effect of Intelligent Manufacturing of Permanent Magnetic Materials Enabled by Industrial Internet Platform

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Abstract

The intelligent manufacturing of permanent magnetic materials driven by the industrial Internet platform is reshaping the traditional cost control paradigm. Its core is to break through the efficiency boundary of process optimization, energy consumption control and quality traceability through the deep integration of data elements and manufacturing processes. This research system analyzes the adaptation logic of industrial Internet technology architecture and permanent magnet material manufacturing scene, builds a three-level collaborative system covering the perception layer, edge layer and cloud platform, and realizes the global dynamic optimization of process parameters and energy flow. In the dimension of process optimization, the multi physics field coupling model based on digital twins breaks through the empirical driven parameter solidification dilemma, and reduces material loss through precise matching of microstructure regulation and macroscopic performance output; At the level of energy consumption control, the penetrating energy profile and equipment energy efficiency health management form an adaptive adjustment mechanism for thermodynamic processes, which fundamentally curb energy redundancy; The quality traceability system relies on blockchain and material gene maps to achieve atomic level attribution of defects and reconstruct the quality cost sharing model of the entire value chain. The study also reveals the practical challenges faced by technology integration, such as physical and chemical process modeling bottlenecks, data sovereignty barriers, and the lack of composite talents. A solution based on cross scale computing framework, federated learning collaborative network, and industry education integration ecology is proposed to provide a theoretical framework and practical paradigm for cost control in intelligent manufacturing of permanent magnet materials.

Keywords

Permanent magnet materials, Industrial Internet, Intelligent manufacturing, cost control.

1. INTRODUCTION

As the core basic material for high-end equipment manufacturing, the production cost control of permanent magnet materials is directly related to the competitiveness enhancement of strategic industries such as new energy and electronic information. The traditional manufacturing model is constrained by the black box effect of processes and experience dependence, facing systemic cost dilemmas such as high energy consumption, low material utilization, and difficulty in tracing quality losses. The rise of industrial Internet technology provides a new way to solve this problem. It is reconstructing the value creation logic of the

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manufacturing system through the deep integration of ubiquitous perception, real-time computing and intelligent decision-making capabilities. Current research mostly focuses on optimizing a single technical link, lacking adaptability analysis of the multi-scale manufacturing characteristics of permanent magnet materials, and even less on deconstructing the inherent mechanism of cost control from a full chain perspective. Based on the deep coupling of industrial Internet technology system and permanent magnet manufacturing scene, this paper systematically studies the adaptation logic of core technology architecture, the generation mechanism of cost control path and its practical constraints. By constructing a collaborative optimization model of process energy consumption quality, the dynamic evolution law of cost factors under data-driven conditions is revealed, providing a solution that combines theoretical depth and practical value for the transformation of intelligent manufacturing.

2. RESEARCH CONTENTS

2.1. Adaptability analysis of industrial Internet technology basic system and permanent magnet material manufacturing scene

2.1.1 Analysis of core technical architecture of industrial Internet

The core technology architecture of industrial Internet relies on the deep collaboration of the Internet of Things perception layer, edge computing layer and cloud based big data platform to build a digital support system covering the whole process of permanent magnetic material manufacturing. The IoT perception layer collects key parameters of the production site in real-time through embedded sensors and intelligent terminal devices, including process variables such as sintering temperature, magnetic field strength, material composition, as well as operating status data such as equipment vibration and energy consumption curves, forming a dynamic data stream of the manufacturing process. The edge computing layer uses the intelligent gateway and lightweight algorithm model deployed at the near end to preliminarily clean, extract features and give immediate feedback to massive real-time data, such as quickly adjusting the power of the heating furnace when temperature fluctuations are detected, or triggering equipment early warning through abnormal vibration identification to achieve local closed-loop optimization of process parameters, thus avoiding the delay problem caused by traditional centralized data processing. The cloud based big data platform integrates heterogeneous data from multiple sources, uses machine learning and digital twin technology to construct process simulation models, optimizes production parameter combinations through historical data training, and coordinates resource allocation in supply chain, energy consumption, and quality traceability from a global perspective. The data flow and instruction flow between different levels are seamlessly integrated through standardized protocols, such as sinking optimized models trained in the cloud to the edge for real-time control, and transmitting complex problems such as multi-objective energy efficiency optimization that cannot be handled by the edge layer back to the cloud for deep computing. This hierarchical collaborative mechanism not only meets the real-time control requirements for high-precision and low latency in permanent magnet material manufacturing, but also provides global decision support for process innovation and cost optimization, forming a closed-loop empowerment path from data perception to intelligent decision-making.

2.1.2 Evaluation of digital requirements and technological compatibility in permanent magnet material manufacturing

The digital demand for permanent magnet material manufacturing stems from the strict requirements for high precision, strong consistency, and dynamic controllability in its complex process chain. The parameter coupling and nonlinear effects in multiple stages, from rare earth raw material ratio to magnet forming and sintering, make it difficult for traditional experience driven models to achieve precise balance between quality and cost [1]. It is urgent to break the

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information silos between processes through the integration of all factor data and construct real-time mapping relationships between process parameters, equipment status, and material properties. The industrial Internet technology system covers the collection of key variables from the temperature field distribution of the smelting furnace to the degree of magnetic field orientation through ubiquitous perception, and ensures the implementation of microsecond level process adjustment with the help of the edge side low delay feedback mechanism, meeting the immediate requirements for the directional control of the microstructure of permanent magnetic materials [2]. At the same time, the multi-dimensional data analysis capability of the cloud can explore the implicit correlation rules between process parameters and magnetic performance indicators, and iteratively optimize the combination of core parameters such as sintering curve and forming pressure through deep learning models, solving the problems of material loss and energy redundancy caused by traditional trial and error methods. At the level of quality traceability, the trusted data chain formed by blockchain and identification resolution technology realizes the full lifecycle binding of raw material batches, process history, and finished product magnetic domain structure, providing reliable basis for defect attribution and process traceability. The technical matching evaluation needs to pay attention to the compatibility of heterogeneous equipment protocols, the stability of sensors under high temperature and high magnetic environment, and the accuracy guarantee of multi-source data fusion, so as to ensure that the industrial Internet architecture can still maintain the integrity of data flow and the effectiveness of control instructions in complex electromagnetic interference and extreme working conditions, thus transforming the theoretical digital potential into the cost control efficiency in actual production.

2.1.3 The underlying support logic of technology integration for cost control

The underlying supporting logic of industrial Internet technology integration for permanent magnet material manufacturing cost control is essentially derived from the deep integration of data elements and physical production, which reconstructs the value creation path of traditional manufacturing. In the field of permanent magnet material manufacturing, the core of technology integration lies in transforming fragmented production knowledge into quantifiable and iterative digital rules, and achieving precise suppression of resource dissipation through closed-loop feedback of multidimensional data streams. The logical starting point is the ubiquitous perception ability for all production factors, which uses high-density deployed sensor networks to penetrate the process black box and capture the micro dynamics of key processes such as rare earth melting, magnetic field orientation, and sintering in real time. It transforms the fuzzy control that originally relied on manual experience into precise control based on physical models. For example, through online analysis of magnetic domain structure evolution data, dynamic correction of magnetic field application parameters can be made to improve orientation consistency, thereby reducing material degradation losses caused by magnetic performance fluctuations.

The collaborative architecture of edge computing and cloud intelligence provides a dynamic optimization engine for cost control. The low latency response capability on the edge side enables adaptive adjustment of process parameters within millisecond time scales, avoiding the accumulation of quality deviations caused by signal transmission delays in traditional centralized control. This real-time correction mechanism not only reduces the scrap rate, but also reduces unplanned energy and material dissipation through a stable process window. The cloud based big data platform integrates device operation, process history, and supply chain information to build a correlation network of global cost influencing factors. It uses deep reinforcement learning to explore the implicit relationship between process parameters, energy consumption curves, and material yield, and generates multi-objective optimized production strategies. For example, when the price of rare earth raw materials fluctuates, the

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system can automatically match the optimal composition ratio and sintering parameter combination to minimize material costs while ensuring magnetic performance.

The deeper value of technology integration lies in the reconstruction of the causal cognitive framework of manufacturing systems. Under the traditional production mode, cost control is often limited to static optimization of local processes, making it difficult to cope with the nonlinear cost derivation problems caused by multi process coupling. The virtual manufacturing space built by the Industrial Internet through the digital twin technology can simulate the resource flow trajectories under different process routes, predict key thresholds such as equipment energy efficiency inflection point, material phase transition threshold in advance, and complete the virtual verification of the optimal cost path before the implementation of the physical world. This predictive optimization capability significantly reduces the cost of trial and error, especially in new product development and process upgrade scenarios, avoiding the huge resource investment brought by traditional repeated experiments.

The quality traceability system embedded with blockchain and identity resolution technology solidifies the foundation of cost control from the reverse dimension. By anchoring data such as raw material batches, process parameters, and test results in an immutable manner on the digital chain, not only is precise traceability of defective products achieved to reduce quality claim risks, but more importantly, a mapping knowledge base of defect causes and process deviations is formed. The continuous accumulation of such data assets shifts cost control from passive remediation to active prevention, identifying cost erosion factors behind weak abnormal signals through machine learning, intervening before quality issues become apparent, and compressing quality costs to a controllable range.

The ultimate form of underlying supporting logic is reflected in the ability of manufacturing systems to evolve autonomously. The cognitive, decision-making and executive closed-loop of industrial Internet construction enables the production process to continuously generate data for self optimization. The process data accumulated in each production cycle is fed back to the parameter update of the control model through feature extraction and knowledge distillation, driving the system to continuously approach the Pareto optimal boundary in a dynamic environment. This spiral upward optimization mechanism ensures that cost control is not a static phased goal, but rather a process of continuous deepening throughout the entire lifecycle of the manufacturing system, ultimately forming an adaptive cost control paradigm through the interaction between technology integration and production practice.

2.2. Cost Control Path

2.2.1 Process optimization to reduce costs

Process optimization and cost reduction in permanent magnet material manufacturing are reflected in the full chain digital deconstruction and reconstruction of complex physical and chemical processes. Its core lies in breaking the empirical solidification state of traditional process parameters through data-driven approaches, achieving precise matching between microstructure control and macroscopic performance output. The essence of process optimization, from temperature field balance control in rare earth alloy melting stage to spatiotemporal accuracy improvement in magnetic field orientation process, is the digital modeling and dynamic intervention of material phase transition dynamics and electromagnetic coupling effects. By embedding sensor networks in key equipment nodes, implicit parameters such as melt viscosity, grain growth rate, and magnetic field gradient distribution can be collected in real time. Combined with digital twin technology, a virtual process space with multi physical field coupling can be constructed to accurately identify the energy efficiency potential range that has not been fully utilized within the traditional process window. For example, in the sintering process, the nonlinear relationship between temperature fluctuations and grain boundary diffusion rate is dynamically analyzed. Through adaptive temperature control

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algorithms, the thermodynamic equilibrium point is stabilized in the critical region where the material densification rate is highest and energy consumption is lowest. This not only avoids grain coarsening loss caused by overheating, but also reduces energy redundancy caused by insulation time.

The cost reduction effect of process optimization is more deeply reflected in the global optimization capability of multi process collaboration. The traditional segmented process control often deviates from the overall goal due to information fragmentation, while the cross process data connection technology based on the industrial Internet can establish the transfer function model of raw material ratio, forming pressure, sintering curve and final magnetic properties. By mining potential association rules in historical production data through machine learning, the system can autonomously generate process parameter combinations that balance material utilization and magnetic performance indicators. For example, it can dynamically adjust formula redundancy during rare earth price fluctuations, or adjust electromagnetic pulse parameters in real-time based on the grain orientation of previous processes during the magnetic field orientation stage, achieving Pareto optimality between material performance and cost consumption. This closed-loop optimization mechanism not only compresses the waste of raw materials caused by traditional trial and error methods, but also pushes the product qualification rate to the theoretical limit through the improvement of process stability.

2.2.2 Fine control of energy consumption

The precise control of energy consumption in the manufacturing of permanent magnet materials is reflected in the full chain penetration governance of energy flow, which essentially reconstructs the traditional extensive energy consumption paradigm through the dynamic matching of energy supply and process demand. In the rare earth smelting process, a thermodynamic digital image of the melt pool based on multimodal sensing technology can be constructed to analyze the nonlinear coupling relationship between the temperature field distribution of the melt and the electromagnetic induction heating power in real time. Through reinforcement learning algorithms, the current frequency and power curve of the induction coil can be dynamically optimized to make the thermal energy transfer efficiency approach the critical point of material phase transition. This adaptive regulation not only avoids the overflow heat loss in traditional constant power heating mode, but also suppresses abnormal grain growth caused by local overheating through real-time feedback of the melt flow state, reducing power consumption while improving material uniformity, forming a bidirectional gain between energy efficiency and product quality.

The breakthrough point in energy consumption control in the sintering process lies in the multidimensional decoupling control of thermodynamic processes. Capture the spatiotemporal evolution characteristics of the three-dimensional temperature gradient inside the furnace through a distributed fiber optic sensing network [4], and construct a dynamic sintering curve optimization engine based on the material densification kinetics model. The system can autonomously decide the optimal combination of heating slope and insulation time based on real-time monitoring of grain boundary diffusion rate and residual stress release status, which not only avoids grain coarsening and energy waste caused by excessive sintering, but also eliminates the ineffective energy consumption caused by "safety redundant heating" in traditional empirical processes. At the same time, the online evaluation of the sealing performance of the furnace body and the leakage compensation algorithm have achieved precise matching of the consumption of protective atmosphere, improving the efficiency of inert gas use to the physical limit.

The refined operation and maintenance of equipment energy efficiency is the underlying guarantee for energy consumption control. Constructing energy efficiency and health profiles of key equipment through feature extraction techniques of high-frequency signals such as

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vibration and current harmonics. When the deterioration of the sealing performance of the vacuum pump group is detected, resulting in a decrease in pumping efficiency, the system can automatically trigger the bearing lubrication compensation or rotor clearance calibration program to avoid the accumulation of ineffective power consumption caused by equipment performance degradation. For the reactive power loss problem in high-power electromagnetic systems, the power factor dynamic correction algorithm is used to match the capacitance compensation in real time, controlling the energy dissipation of transient electromagnetic fields within the theoretical lower limit of process requirements. This energy efficiency protection mechanism that runs through the entire lifecycle of the equipment fundamentally curbs the continuous erosion of hidden energy loss.

2.2.3 Quality traceability cost compression

The cost compression of quality traceability in permanent magnet material manufacturing is reflected in the deep evolution of defect traceability capability and the systematic blockage of quality loss chain. Its core lies in constructing a digital gene map that runs through the entire life cycle to achieve accurate attribution and preventive intervention of quality problems. Through quantum dot labeling technology and blockchain anchoring of heterogeneous data from multiple sources, each raw material batch is assigned a unique material information fingerprint during the melting stage. The purity fluctuations of rare earth elements, melt flow trajectories, and grain boundary formation characteristics are written into a distributed ledger with nanometer level accuracy. When local demagnetization is detected in the magnetic performance testing after the sintering process, the system can trace back to the temperature gradient anomaly or electromagnetic interference event during the magnetic field orientation in the melting stage, accurately locate the spatiotemporal coordinates of the process deviation, and avoid the sunk costs caused by batch material degradation in traditional sampling detection mode. This atomic level traceability capability compresses the traceability granularity of quality issues from the process level to the equipment action level, greatly reducing the associated scrap losses caused by fuzzy attribution.

In the dimension of quality cost reconstruction, the traceability system forms a causal inference network of process defects through knowledge distillation. Each abnormal event triggers a self-organizing root cause analysis engine to cross modal correlate unstructured data such as device vibration harmonics and electromagnetic environmental noise with material phase transition characteristics, uncovering hidden failure modes that have not been recognized in traditional quality control. For example, after identifying the hysteresis correlation between slight fluctuations in the pH value of the cooling water and micro cracks in the magnet, the system autonomously optimizes the frequency of water quality monitoring and establishes a dynamic adjustment mechanism for the buffer tank, compressing the improvement process that originally required several batches of experimental verification into a real-time closed-loop response. This continuously evolving quality knowledge base enables defect prevention measures to break through the limitations of experience, significantly reducing the iteration cost of repetitive quality accidents.

Deeper cost compression stems from the collaborative optimization of quality traceability and supply chain. Through the full industry chain identification analysis system, the smelting process parameters of raw material suppliers and the performance data of the manufacturing end form a two-way feedback channel. When the coercivity of a certain batch of neodymium iron boron magnets is abnormally reduced, the system can penetrate to the extraction agent ratio record of the rare earth separation plant, adjust the compensation coefficient of the sintering process of the factory in linkage, and trigger the process warning on the supplier side [5]. This cross enterprise level quality traceability network extends the traditional cost of quality from a single manufacturing process to the entire value chain. Through collaborative

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calibration of upstream and downstream process parameters, it avoids the accumulation of secondary processing costs caused by hidden defects in raw materials. The dynamic settlement mechanism of quality guarantee deposit based on smart contracts precisely quantifies the quality responsibility to each production unit, forcing the improvement of the quality level of the entire chain to form a benign ecology of cost sharing.

3. CHALLENGES AND COUNTERMEASURES

3.1. Realistic difficulties

The core dilemma of intelligent manufacturing of permanent magnetic materials enabled by the industrial Internet platform is that the deep coupling between the physical world and the digital space has not yet broken through multiple barriers. The fragmentation of heterogeneous device protocols in production sites leads to blind spots in process data collection, and real-time analysis of key process variables such as dynamic temperature field distribution and magnetic field orientation electromagnetic parameters in melting furnaces is still limited by sensor accuracy and anti-interference ability, making it difficult for the fidelity of digital twin models to support process optimization decisions. The deeper contradiction lies in the computability bottleneck of complex physical and chemical processes, and the multiscale modeling of rare earth phase transition dynamics and microscopic magnetic domain evolution still relies on empirical formula simplification, which leads to data-driven algorithms easily falling into local optimal traps in scenarios such as sintering curve optimization. In addition, the construction of material gene maps required for cross process quality traceability has encountered lagging micro characterization techniques, and the mapping relationship between nanoscale grain boundary features and macroscopic magnetic properties has not been fully decoded, which restricts the accuracy of defect root cause analysis. The data sovereignty barrier at the level of industrial chain collaboration is also significant. The closed nature of process parameters and quality data between upstream and downstream enterprises hinders the optimization of the entire value chain cost, while the lack of composite talents further amplifies the technical landing resistance.

3.2. Solution

To solve the above dilemma, it is necessary to build a digital foundation that penetrates the entire manufacturing chain, achieve protocol decoupling and data ubiquitous connection of multi-source heterogeneous devices through edge intelligent gateways, and enhance process perception capabilities under extreme working conditions such as high temperature and strong magnetic fields by combining metasurface sensing technology. At the level of mechanism model construction, material informatics and reinforcement learning algorithms are integrated to establish a cross scale computational framework that couples grain growth dynamics and electromagnetic fields. The real-time calibration mechanism of digital twins is used to reduce the deviation between theoretical models and actual processes. To address the challenge of quality traceability, a grain boundary feature analysis system based on electron backscatter diffraction and machine learning is developed, which converts the microstructure evolution trajectory into traceable digital gene sequences. In terms of industrial chain collaboration, the use of federated learning technology to build a distributed process optimization network enables cross factory energy consumption and quality knowledge sharing while ensuring enterprise data sovereignty.

4. CONCLUSION

The intelligent manufacturing of permanent magnetic materials enabled by the industrial Internet platform shows significant cost control effect. Its essence is to reconstruct the value

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transmission chain of the manufacturing system through the full penetration of data flow. The research shows that the collaborative architecture of IoT sensing and edge computing realizes the millisecond level dynamic optimization of process parameters, and improves the precision of rare earth phase change dynamics control to submicron scale; The multi-objective decision model driven by digital twins breaks through the limitations of traditional local optimization and establishes a global balance point between material performance and resource consumption. The blockchain based quality traceability system not only compresses the cost of defect attribution, but also forms a quality cost sharing ecosystem through knowledge sharing at the industry chain level. However, the implementation of technology still faces challenges such as extreme working condition sensing bottlenecks and modeling biases in multi physics field coupling. Further development of metasurface sensing technology and cross scale computing frameworks is needed to enhance the physical fidelity of digital models. Future research should focus on the construction of distributed optimization networks supported by federated learning, unleashing the potential for collaborative cost reduction across the entire industry chain while ensuring data sovereignty. The intelligent transformation of permanent magnet material manufacturing is not only a paradigm shift in cost control, but also a key milestone for high-end manufacturing to transition from experience driven to cognitive driven.

REFERENCES

[1] Wu Yiding, Yang Yang Evaluation of Profit Quality of Rare Earth Listed Companies Based on Factor Analysis: Empirical Evidence from the Shanghai and Shenzhen Stock Exchanges [J]. Finance and Accounting Communications, 2015 (32): 21-23.

[2] Ban Fei, Lian Guangkun, Gu Guobiao, et al. Research on Predictive Torque Control Strategy of Single Vector Decoupling Model for Permanent Magnet Synchronous Motor [J]. New Technology of Electrical Energy, 2020, 39 (12): 44-51.

[3] Li Yaohua, Qin Hui, Su Jinshi et al. Study on Cost Function of Finite Set Model Predictive Torque Control for Surface mounted Permanent Magnet Synchronous Motor [J]. Motor and Control Applications, 2019, 46 (9): 12-18.

[4] Tu Wencong, Luo Guangzhao, Liu Weiguo. Finite control set model predictive current control of permanent magnet synchronous motor based on fuzzy dynamic cost function [J]. Journal of Electrical Engineering, 2017, 32 (16): 89-97.

[5] Wu Junliang and Liu Fei's Control and Decision Model for Macroeconomic Operations [J]. Control and Decision. 2004 (06): 12-13.