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Intelligent Manufacturing Technology for New Energy Vehicles in the Context of Industry 4.0

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Abstract:
The new energy vehicle industry, as a fusion of high-end manufacturing and green development, has become an important breakthrough in the Fourth Industrial Revolution. This study aims to explore the research and application of intelligent manufacturing technology for new energy vehicles in the context of Industry 4.0, and to analyse the pain points and challenges in the process of digital transformation. By establishing a key technology system based on Industry 4.0 technology empowerment pathways, a series of intelligent manufacturing solutions for new energy vehicle production and research and development have been proposed. Optimise R&D and production through Digital Twin, enabling system modelling and parameter verification in a virtual environment to improve production efficiency and reduce energy consumption and emissions. Utilising artificial intelligence technology to achieve quality control throughout the entire life cycle, continuously improving product quality control standards and reducing the rate of defective products. In flexible production lines, exploring the combination of 5G networks and dynamic scheduling algorithms to optimise production processes through real-time data processing and analysis, thereby enhancing manufacturing flexibility. Taking the case of intelligent upgrading of battery factories of new energy vehicle enterprises as an example, this paper conducts an in-depth analysis of the technical challenges faced in the process of intelligent manufacturing and future development directions, summarises current technical bottlenecks, and looks ahead to the integration trends of cutting-edge technologies.

Keywords: Intelligent Manufacturing, New Energy Vehicles, Artificial Intelligence

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1. Introduction

Driven by the dual forces of carbon neutrality targets and digital transformation, the global manufacturing industry is undergoing profound restructuring.The new energy vehicle industry, as a strategic intersection of high-end manufacturing and green technology, has become the core vehicle for the implementation of Industry 4.0.The industry currently faces systemic challenges such as production efficiency bottlenecks, inefficient supply chain coordination, and a surge in demand for personalised customisation. There is an urgent need to achieve a breakthrough in manufacturing paradigms through the integration of cutting-edge technologies.Intelligent manufacturing technologies such as digital twins, artificial intelligence, 5G communications, and blockchain are driving the restructuring of R&D and production processes and the transformation of supply chain systems. These technologies provide new ways to shorten delivery cycles, reduce energy consumption fluctuations, and improve yield rates through virtual simulation optimisation, real-time quality control, dynamic resource scheduling, and trusted data collaboration. Against this backdrop, exploring the integrated application mechanism of Industry 4.0 technology clusters in new energy vehicle manufacturing has urgent practical significance for breaking through the bottlenecks of industrial upgrading. This study focuses on technology-enabled pathways and pain points in industrial practice, with the aim of constructing a future-oriented smart manufacturing technology framework.

2. Industry 4.0 empowers new energy vehicle intelligent manufacturing

2.1 Industry 4.0 Technology Enabling Paths

Against the backdrop of the current global economic transformation and technological change, the new energy vehicle market is experiencing unprecedented growth. In particular, in 2023, the global penetration rate of new energy vehicles exceeded 18%[1]. However, manufacturing efficiency bottlenecks accompanying market expansion have become increasingly apparent, particularly in terms of longer delivery cycles and the complexity of mixed-model production lines. This phenomenon not only puts operational pressure on companies but also limits their ability to respond quickly to market demand.

From a technical perspective, traditional manufacturing models are no longer able to meet the demands of personalised customisation. For example, taking Tesla's Model 3 as an example, the issue of order response delays highlights the shortcomings of the existing system. Fluctuations in battery production yields, especially CATL's publicly reported 5% rework rate due to welding defects, further increase uncertainty in the manufacturing process. The global chip shortage has exposed inefficiencies in supply chain coordination. Manufacturing companies often lack the ability to dynamically adjust their BOM tables, which has contributed to delays in production planning.

2.2 Key Technology System for Intelligent Manufacturing of New Energy Vehicles

The key technology system for intelligent manufacturing of new energy vehicles plays a crucial role in the current global Industry 4.0 context [2]. The core of this system lies in its incorporation of multiple advanced production and R&D technologies, which play an indispensable role in improving production efficiency and product quality. Digital Twin is a new R&D and production optimisation technology that can monitor production processes in real time and perform predictive analysis by creating virtual copies of physical entities. The application of this technology means that the entire life cycle, from product design to production execution, can be efficiently verified in a virtual environment. For example, Tesla, a new energy vehicle manufacturer, achieved a significant 80% reduction in physical prototype verification costs by using a battery pack thermal-mechanical-electrical coupled simulation model built on ANSYS Twin Builder. This significantly reduced physical testing time and greatly improved the speed and efficiency of innovation.

2.3 Intelligent Manufacturing Core Manufacturing System and Solutions

In the R&D and production process of new energy vehicles, Digital Twin technology (Digital Twin) is undoubtedly a key tool to achieve efficiency improvement and cost control [3]. By creating virtual copies of physical entities, Digital Twin technology enables companies to optimise product design and production processes without the need for extensive physical trial and error, thus significantly reducing the cost of physical prototype validation in the R&D process.For example, Tesla Motors successfully reduced physical testing requirements by up to 80% by constructing a thermal-mechanical-electrical coupled simulation model of the battery pack using ANSYS Twin Builder. This not only effectively reduced R&D costs but also accelerated the speed at which the product was brought to market..

In addition to product development, digital twins also play an important role in the optimisation of production processes. With the help of virtual debugging tools such as Siemens Process Simulate, companies are able to compress the cycle time for production line logic verification from the traditional 30 days to 7 days. This reduction in time comes from real-time monitoring and intelligent analysis of the production process, which enables potential bottlenecks to be identified and improved in a timely manner.

2.4 AI-driven Quality Control

In the context of "Industry 4.0", the rapid development of intelligent manufacturing technology for new energy vehicles has become an urgent need for the transformation of the automotive industry [4]. With the evolution of the global automotive industry to the direction of electrification, intelligence and network connectivity, new energy vehicles are gradually emerging as an important market player [5]. In this process, intelligent manufacturing technology plays a crucial role, especially in improving production efficiency, optimising resource allocation, and ensuring quality control [6]. On the one hand, intelligent manufacturing relies on the "Digital Twin" technology (Digital Twin) to help achieve the deep integration of R&D and production, through real-time data feedback and simulation prediction, significantly improve R&D efficiency and product quality. For example, Tesla's automobile manufacturing company has successfully shortened the R&D cycle by 20% and increased the first pass rate of products by 15% through the introduction of Digital Twin [7]. On the other hand, the application of Artificial Intelligence (AI) in quality control embodies another important dimension of smart manufacturing. The AI intelligent inspection system based on big data analysis is able to identify defects in the production process in real time, so that timely adjustments can be made to reduce rework rates and improve customer satisfaction.

At the same time, with the introduction of the 'G+ flexible production line' concept, companies are facing new challenges in production scheduling. Flexible production lines based on dynamic scheduling algorithms can not only meet the production needs of different models and configurations, but also make flexible adjustments based on real-time data. The effective implementation of this production model has significantly improved production line utilisation, thereby meeting customer needs while reducing production costs. On the other hand, the introduction of blockchain technology has provided new solutions for supply chain collaboration. This technology optimises collaboration across all stages of raw material procurement, production, and distribution by enhancing information transparency, traceability, and immutability. This not only enhances trust among all parties in the supply chain but also improves overall efficiency.

In practical application, overcoming existing technical bottlenecks has become an urgent issue for enterprises to address. Particularly in areas such as data integration, system interconnectivity, and information security, significant challenges remain. For example, some enterprises have found that during the implementation of smart manufacturing, the lack of uniform standards for their internal information systems has made data sharing more difficult. In such cases, it is particularly important to develop targeted standards and regulations.

From the perspective of cutting-edge technology integration, the future of intelligent manufacturing for new energy vehicles will show a more diversified trend [8]. Among these, the combination of 5G communication technology (5G) and the Internet of Things (IoT) will promote the interconnection of more intelligent devices and systems, and through real-time data analysis, achieve more refined production management. For example, the high speed and low latency characteristics of 5G technology enable vehicles on the production line to seamlessly connect with their intelligent systems, greatly improving production response speed. With the continuous integration of a large number of cutting-edge technologies, the future of intelligent manufacturing for new energy vehicles is full of infinite possibilities. Companies need to continuously explore the potential value of these technologies in order to achieve a first-mover advantage in the global market.

2.5 Dynamic Scheduling of G+ Flexible Production Line

In the current context of Industry 4.0, the bottlenecks faced by traditional production lines during changeovers limit overall production efficiency, particularly in the new energy vehicle sector, where prolonged changeover times significantly increase delivery cycles and production costs [9]. Insufficient changeover time not only affects the production line's ability to flexibly respond to market changes but also leads to inefficient use of production resources, thereby inhibiting improvements in production capacity. Currently, some factories experience changeover times as long as 8 hours when switching vehicle models, severely limiting the efficiency of mixed-model production lines.

In order to solve this technical bottleneck, it is necessary to introduce advanced 5G communication technology and flexible production line scheduling mechanism to achieve Dynamic Scheduling and optimal allocation of resources. 5G undoubtedly brings new opportunities for intelligent manufacturing, and its ultra-reliable and low-latency communication (URLLC) characteristics can effectively improve the efficiency of the coordination between the

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equipment to ensure that the orders are accurately and quickly transmitted. transmission. In this context, through the introduction of joint planning and decision-making models (Optimization Algorithms), the dynamic deployment of equipment and human resources can be achieved, which greatly shortens the changeover time.

2.6 Blockchain-enabled Supply Chain Collaboration

Against the backdrop of Industry 4.0, the rapid development of intelligent manufacturing in the new energy vehicle (NEV) sector has driven profound changes in supply chain management [10]. Blockchain technology, as an emerging information storage and transmission technology, has demonstrated exceptional potential in optimising supply chain collaboration. Its decentralised, immutable, and transparent characteristics make it a crucial tool for enhancing the efficiency and reliability of the NEV industry's supply chain.

Taking the supply of parts as an example, the manufacturing process of new energy vehicles is extremely complex, with a high dependence on various raw materials and components. Supply chain management empowered by blockchain can achieve comprehensive tracking of the source, production process and transport status of components. For example, taking Tesla electric car manufacturer as a case study, it adopts blockchain technology to empower the supply chain of battery components, and the data information of the whole process, from raw material procurement to manufacturing to product delivery, can be recorded in real time on the blockchain. In this way, it can not only improve the real-time information transmission but also ensure that the information in each link is true and effective, thus reducing the risk of potential counterfeiting.

Further analysis, the application of blockchain in the supply chain of new energy vehicles is also reflected in the efficiency of capital flow. Through the setting of a Smart Contract, the automated settlement of funds between participants can be realised, reducing human intervention. This mechanism is crucial for reducing transaction costs and improving the efficiency of capital turnover. For example, in the case of Tesla's new energy vehicle supply chain, the blockchain-driven Smart Contract can automatically trigger payment after each component delivery and acceptance, thus realizing zero-delay fund flow. This alleviates, to a certain extent, the cash flow pressure that exists in the traditional supply chain and enhances the liquidity of suppliers.

Blockchain technology also shows new application prospects in Product Lifecycle Management (PLM) in new energy vehicle manufacturing [11]. By recording the entire lifecycle data of each vehicle from production, delivery to use and maintenance, all parties involved can access complete and credible data in real time. This idea of using data-driven management provides important support for companies to achieve Lean Production while improving product quality and customer satisfaction.

Although blockchain technology shows great potential and advantages in the new energy vehicle supply chain, its implementation also faces many challenges. For example, the lack of technical standards, trust mechanisms for cross-enterprise data sharing, and coordination mechanisms among participants may all affect the actual application of blockchain technology. Therefore, in order to truly implement and promote blockchain technology, it is necessary to strengthen cooperation among enterprises, establish relevant industry standards and regulatory frameworks, and promote the sustainable development of blockchain technology in the new energy vehicle supply chain industry.

Blockchain-based supply chain collaboration in the new energy vehicle industry not only enhances efficiency in product manufacturing and distribution but also provides new directions and possibilities for the industry's future development. As the technology continues to mature and practical applications deepen, blockchain will undoubtedly play an increasingly important role in enhancing the overall efficiency of smart manufacturing in the new energy vehicle sector [12].

2.7 Intelligent Upgrading of Battery Factory of New Energy Vehicle Enterprises

In the field of new energy vehicle manufacturing, especially in the intelligent upgrading process of the battery factory of Tesla new energy vehicle enterprises, there are many technical challenges, and there is an urgent need to deal with these bottlenecks through technological innovation [13]. The current yield fluctuation problem in the battery manufacturing process has become a key factor restricting the overall capacity improvement, and the yield fluctuation at this stage can reach ±5%. Behind this phenomenon is not only the complexity of the production process itself, but also the increasingly stringent quality standards. In this context, the use of flexible intelligent manufacturing technology has become a necessary path, through the in-depth analysis and optimisation of the existing manufacturing process, to explore innovative materials and methods, can effectively reduce the variation in the production process, improve the product qualification rate [14].

Energy consumption is also an important factor that can-not be ignored. In the battery manufacturing process, energy consumption accounts for as much as 25% of the total cost. An energy consumption monitoring system based on digital twin technology can optimise the start-stop strategy for compressed air in real time, thereby saving 18% of electricity. Simulating and predicting the thermal-mechanical-electrical coupling effects of battery modules can help further reduce energy consumption and improve economic efficiency and environmental friendliness.

However, the implementation of smart manufacturing has not been smooth sailing, with data security issues becoming increasingly prominent. With the popularisation of the Industrial Internet, the annual growth rate of cyber attacks has reached 120% [15]. In response to this situation, the introduction of federated learning technology and homomorphic encryption schemes can help ensure data security during transmission and storage, thereby paving the way for the widespread application of smart manufacturing.

3. Conclusion

This study shows that the integration of core Industrial 4.0 technologies provides key support for improving the manufacturing efficiency, quality control accuracy, and supply chain coordination efficiency of new energy vehicles. Digital twin technology significantly reduces R&D verification costs and accelerates production line debugging; AI-driven quality control systems have improved defect detection rates; 5G-enabled flexible production line dynamic scheduling has optimised resource allocation; and blockchain technology has enhanced supply chain transparency and trust. However, the implementation of these technologies still faces significant bottlenecks: data security risks associated with the popularisation of the industrial Internet need to be addressed; inconsistent standards between systems lead to data silos and collaboration barriers; and yield fluctuations and high energy consumption in flexible manufacturing need to be further optimised. Future research and practice should focus on: developing enhanced data security architectures based on federated learning and homomorphic encryption; promoting the establishment of unified data standards and interface specifications across enterprises and systems; deepening the application of 5G+edge computing in real-time dynamic scheduling; exploring the expanded value of blockchain in supply chain finance and lifecycle-wide trusted data management; Continuously optimising the predictive and regulatory capabilities of digital twin models for complex manufacturing processes to achieve a more efficient, reliable, and sustainable intelligent manufacturing system for new energy vehicles.4

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