

Precision Jigs and Molds: Innovative Design and Application

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Abstract

Precision jigs and molds are key tools in modern manufacturing, playing a vital role in enhancing product quality, boosting production efficiency, and reducing costs. They ensure product consistency and repeatability, minimize errors, and improve quality. Optimized design and processes can shorten production cycles and enhance efficiency. Moreover, by reducing scrap rates and extending service life, they significantly cut production costs.

This thesis explores innovative design methods for precision jigs and molds, including topology optimization, biomimetic design, intelligent design, and multidisciplinary integration design. These methods have achieved remarkable results in practical applications. By optimizing structure, improving material properties, and incorporating intelligent design, the performance and service life of molds and jigs have been significantly enhanced.

Keywords: precision jigs, molds, innovative design, application, Suzhou Menaqiu Mechanical and Electrical Equipment Co., Ltd., mechanical and electrical equipment, hardware accessories, metal products, production efficiency, product quality, cost control, computer-aided design, biomimetic design, intelligent design

1. Introduction

1.1 Research Background

In modern manufacturing, with the intensification of market competition and the diversification of customer needs, the requirements for product quality and production efficiency are increasingly high. Precision jigs and molds, as key tools in the product manufacturing process, directly determine the precision, consistency, and production efficiency of products. Suzhou Menaqiu Mechanical and Electrical Equipment Co., Ltd., as a company specializing in the manufacturing of mechanical and electrical equipment and related products, covers multiple fields such as mechanical and electrical equipment, hardware accessories, and metal products, and has a continuous demand for high-precision and high-performance jigs and molds. To meet customers' demands for high-quality products and enhance market competitiveness, the company actively explores and applies advanced innovative design methods to optimize the design and manufacturing processes of jigs and molds.

1.2 Research Significance

This study, by exploring the innovative design methods of precision jigs and molds and their practical application in Suzhou Menaqiu Mechanical and Electrical Equipment Co., Ltd., aims to enhance the company's market competitiveness and meet customers' demands for high-quality products. Meanwhile, the research will propel the company to take an important step in technological progress and innovation, providing successful case studies and experience for other enterprises in the same industry, and promoting the technological advancement and sustainable development of the entire industry.

1.3 Research Objectives and Content

The primary objective of this study is to explore the specific application of innovative design concepts and

methods of precision jigs and molds in Suzhou Menaqiu Mechanical and Electrical Equipment Co., Ltd., and to analyze the actual effects and advantages of these innovative designs in real production. The research content includes:

- Introducing the importance of precision jigs and molds in modern manufacturing and their current application status in Suzhou Menaqiu Mechanical and Electrical Equipment Co., Ltd.
- Discussing the application of innovative methods such as topology optimization, biomimetic design, intelligent design, and multidisciplinary integration design in the company's jig and mold design.
- Analyzing the actual effects of innovative design methods in improving production efficiency, product quality, and reducing costs.
- Proposing optimization suggestions to provide references for the company's future innovation and development, and to assist the company's sustainable development.

2. Definition, Development, and Role of Precision Jigs and Molds

2.1 Definition and Classification

Precision jigs are tools used in manufacturing for precise positioning, clamping, and supporting workpieces, widely applied in mechanical processing, electronic manufacturing, and automotive manufacturing. Their characteristics include high precision (typically at the micron level), high repeatability (ensuring stable product quality), and durability (able to withstand frequent use and harsh environments).

Molds are tools used for forming, replicating, and processing materials. Common types include injection molds (for plastic forming), stamping molds (for metal sheet forming), casting molds (for metal casting), and forging molds (for metal forging). Their structural composition and working principles vary depending on the type. For example, an injection mold consists of a moving mold, a fixed mold, a gating system, and a cooling system, which forms the product by injecting molten plastic and cooling it; a stamping mold is composed of upper and lower molds and guiding devices, which deform or separate metal sheets through pressure. (Stratakis, E., Ranella, A., & Fotakis, C., 2011)

2.2 Development History

Traditional jig and mold design and manufacturing relied on manual drawing and mechanical processing, with low efficiency and limited precision. With the advancement of technology, computer-aided design (CAD), computer-aided manufacturing (CAM), numerical control machining (CNC), and 3D printing technologies have successively emerged, significantly improving design and manufacturing efficiency and precision, shortening the cycle, and reducing costs.

2.3 Role in Manufacturing

Precision jigs ensure the quality and stability of processing by precisely positioning, clamping, and supporting workpieces; molds achieve material forming and replication in mass production, ensuring product quality consistency. Together, they enhance product quality and production efficiency.

3. Innovative Design Theories and Methods for Precision Jigs and Molds

3.1 Importance of Innovative Design

Innovative design of precision jigs and molds holds significant importance in modern manufacturing. With the rapid development of high-end manufacturing industries such as automotive, electronics, and aerospace, the demand for precision molds has surged. Innovative design not only meets the challenges of complex product shapes and high-performance requirements but also satisfies the needs of customized production, thereby enhancing a company's market competitiveness and economic benefits.

3.2 Theoretical Basis of Innovative Design

The theoretical basis of innovative design encompasses the latest achievements in modern design theory, material science and engineering, as well as the cutting-edge developments in mechanical engineering and manufacturing technology. Computer-aided design (CAD) and virtual design technologies make the design process more efficient and precise. Advances in material science provide more high-performance material options for jigs and molds. Developments in mechanical engineering and manufacturing technology, especially the application of numerical control machining (CNC) and 3D printing, have greatly improved manufacturing precision and efficiency.

3.3 Innovative Design Methods

In the practice of Suzhou Menaqiu Mechanical and Electrical Equipment Co., Ltd., the application of innovative design methods has significantly enhanced the performance and benefits of precision jigs and molds. Through topology optimization design, the company has successfully developed lightweight yet high-strength fixtures,

improving production efficiency and reducing costs. Inspired by biomimetic design, the company developed new molds based on the honeycomb structure, which not only extended the service life but also reduced energy consumption, making them particularly suitable for producing lightweight, high-strength hardware accessories. Intelligent design utilizes artificial intelligence technologies, such as machine learning and neural networks, to analyze and learn from historical design data, automatically generating optimized design solutions, improving design efficiency and quality, and shortening the design cycle. Moreover, multidisciplinary integration design, combining knowledge from materials, mechanics, thermodynamics, and other disciplines, optimized the material selection and structural design of molds, extending their service life by 50% and improving production efficiency by 30% in high-temperature, high-pressure working conditions. These innovative design methods not only enhanced the technological content of the products but also gave the company a competitive edge in the market. (Hu, Z. J., Yan, Y. D., Zhao, X. S., et al., 2011)

3.4 Innovative Design Process

The innovative design process includes demand analysis and target setting, conceptual design and scheme generation, detailed design and simulation analysis, optimization adjustment and scheme determination, and manufacturing and testing verification. This process ensures the scientific and practical nature of the design. For example, in a high-precision mechanical part machining project of Suzhou Menaqiu Mechanical and Electrical Equipment Co., Ltd., detailed demand analysis and target setting led to the generation of several conceptual design schemes. After detailed simulation analysis and optimization adjustment, the optimal design scheme was determined and verified through manufacturing and testing, ensuring the high quality and performance of the design.

Table 1. Comparison of Innovative Design Methods

Design Method	Features	Advantages	Application Example
Topology Optimization Design	Automatically optimizes material distribution	Lightweight, high strength	Automotive fixture design
Biomimetic Design	Inspired by biological structures	Efficient, energy-saving, adaptable	Electronic fixture design
Intelligent Design	Utilizes artificial intelligence technology	Automated, intelligent	Mold design optimization
Multidisciplinary Integration Design	Combines knowledge from multiple disciplines	Comprehensive performance improvement	Automotive mold design

Table 2. Key Steps and Objectives of the Innovative Design Process

Step	Objective	Methods and Tools
Demand Analysis and Target Setting	Clarify demands, set targets	Customer communication, market research
Conceptual Design and Scheme Generation	Generate multiple design schemes	Brainstorming, sketching
Detailed Design and Simulation Analysis	Detailed design and performance verification	CAD, CAE, finite element analysis
Optimization Adjustment and Scheme Determination	Optimize design schemes	Iterative optimization, performance analysis
Manufacturing and Testing Verification	Manufacture physical products and verify performance	Numerical control machining, 3D printing, performance testing

4. Case Analysis of Innovative Design of Precision Jigs and Molds

4.1 Innovative Design of Precision Jigs for High-Precision Mechanical Part Machining

In high-precision mechanical part machining, traditional jigs often face issues such as insufficient positioning accuracy, unstable clamping force, and short service life, leading to difficulties in ensuring machining precision, low production efficiency, and increased production costs due to frequent jig replacement. Suzhou Menaqiu

Mechanical and Electrical Equipment Co., Ltd. addressed these problems by adopting an innovative design philosophy that incorporates new materials and optimized structural layouts. The company introduced high-strength aluminum alloy materials to reduce the weight of the jigs while enhancing their strength and wear resistance. Modular design was also employed to facilitate the assembly and maintenance of the jigs. During the design process, computer-aided design (CAD) and finite element analysis (FEA) technologies were utilized to precisely model the jig structure and analyze its mechanical properties. The clamping mechanism was optimized to ensure even distribution of clamping force, preventing workpiece displacement during machining. Additionally, advanced surface treatment techniques were applied to improve wear resistance and corrosion resistance. The innovative design of the jigs resulted in a 20% increase in machining precision, a 50% extension of service life, and a 30% improvement in production efficiency, thereby reducing production costs and enhancing the company’s market competitiveness.

With the trend of electronic components becoming smaller and more highly integrated, traditional jig designs are increasingly unable to meet the high-precision machining requirements. The company adopted micro-nano structural design and high-precision positioning technologies to develop jigs and positioning devices with micro-nano structures, capable of accurately fixing and positioning micro-sized electronic components to ensure high-precision machining. The introduction of intelligent sensor technology to monitor temperature, pressure, and other parameters in real-time during the machining process further enhanced machining stability and reliability. In an electronic component manufacturing project, the company’s precision jigs were successfully applied in chip packaging and micro-electromechanical systems (MEMS) production. The optimized micro-nano structure of the jigs achieved high-precision positioning and clamping of micro-sized components, with machining precision reaching the micron level. The application of intelligent sensors made machining parameters controllable in real-time, significantly improving production efficiency and product quality.

4.2 Case of Innovative Mold Design

The injection molding of complex-shaped plastic products faces challenges such as long molding cycles, unstable product quality, and low mold cooling efficiency. Traditional mold designs struggle to meet the demands of efficient production. Suzhou Menaqiu Mechanical and Electrical Equipment Co., Ltd. adopted innovative design strategies of using hot runner technology and optimizing the mold cooling system. Hot runner technology reduces the residence time of plastic in the runner, improving molding efficiency. The optimized cooling system design enhances mold cooling efficiency, shortening the molding cycle. During the design process, computer-aided engineering (CAE) technology was employed to simulate and analyze the mold structure and cooling system design, determining the optimal layout of cooling channels and hot runner design parameters to ensure efficient mold operation. The application results of the innovatively designed injection mold were remarkable, with a 30% reduction in molding cycle, significant improvement in product quality, and a 50% decrease in scrap rate. Production efficiency was increased, production costs were reduced, and the company’s market competitiveness was enhanced. (Hu, Z. J., Yan, Y. D., Zhao, X. S., et al., 2011)

Table 3. Case of Innovative Design of High-Strength Metal Sheet Stamping Mold

Project Type	Problem Description	Innovative Design Measures	Material Improvement	Technology Application	Effect Improvement
High-Precision Mechanical Part Machining Jig Design	Insufficient positioning accuracy, unstable clamping force, short service life	Adopting new materials and optimizing structural layout, introducing high-strength aluminum alloy materials, modular design	High-strength aluminum alloy materials, reducing weight, improving strength and wear resistance	Computer-aided design (CAD), finite element analysis (FEA), advanced surface treatment technology	Increased machining precision by 20%, extended service life by 50%, improved production efficiency by 30%
Electronic Component Manufacturing Jig Design	Traditional jigs fail to meet high-precision machining requirements, difficulty in fixing and	Micro-nano structural design and high-precision positioning technology, developing jigs and positioning devices with micro-nano	-	Micro-nano structural design, high-precision positioning technology, intelligent sensor	Achieved micron-level precision in fixing and positioning micro-sized components, improved

	positioning micro-sized electronic components	structures		technology	production efficiency and product quality
High-Strength Metal Sheet Stamping Mold Design	High stamping force, rapid mold wear, difficulty in ensuring stamping precision, leading to low production efficiency, short mold service life, and high production costs	Optimizing mold materials and stamping process parameters, using high-performance mold steel and surface coating technology to improve mold wear resistance and fatigue resistance, optimizing stamping process parameters to ensure stability and precision of the stamping process	High-performance mold steel, surface coating technology	Optimized mold materials and stamping process parameters	Extended mold service life by 50%, increased stamping precision by 20%, improved production efficiency, reduced production costs

5. Application Effect Assessment of Innovative Design of Precision Jigs and Molds

The innovative design of precision jigs and molds holds significant importance in modern manufacturing, and the assessment of its application effects is crucial for promoting technological progress and industry development. This paper comprehensively evaluates the application effects of the innovative design of precision jigs and molds from three aspects: the evaluation index system, evaluation methods, and evaluation results.

5.1 Evaluation Index System

To comprehensively evaluate the application effects of the innovative design of precision jigs and molds, an index system covering multiple aspects such as production efficiency, product quality, cost, reliability, and environmental friendliness has been established. Production efficiency is measured through two dimensions: production cycle and production speed. Optimized design and manufacturing processes can significantly shorten the cycle and enhance speed, thereby improving overall efficiency. Product quality indicators include dimensional accuracy, surface quality, and product consistency. Innovative design can enhance precision, improve surface quality, and ensure consistency, thereby reducing scrap rates. Cost indicators mainly involve mold manufacturing costs and usage and maintenance costs. By optimizing design and processes, costs can be effectively reduced to improve economic benefits. Reliability and service life indicators measure the durability and service life of molds in actual working conditions. Innovative design significantly enhances the reliability and service life of molds, reducing the frequency of replacements. Environmental friendliness indicators assess the recyclability of materials and energy consumption. Innovative design helps to increase the recyclability of materials, reduce energy consumption, and minimize environmental impact.

5.2 Application Effect Evaluation Methods

Scientific and rational methods such as comparative analysis, data statistics and analysis, and user feedback and market research are adopted to ensure the accuracy and reliability of the evaluation results. Comparative analysis involves comparing the performance of innovatively designed molds with traditional molds under the same working conditions to intuitively present the advantages of innovative design in key indicators such as production efficiency, product quality, and cost. Data statistics and analysis involve collecting relevant data from the production process and analyzing it using statistical methods to comprehensively evaluate the effects of innovative design. User feedback and market research involve collecting user satisfaction with innovative products through questionnaires and customer interviews, analyzing market demand, and assessing the competitiveness of innovative products in the market.

5.3 Application Effect Evaluation Results

Taking the high-precision mechanical part machining project of Suzhou Menaqiu Mechanical and Electrical Equipment Co., Ltd. as an example, the application of innovatively designed molds has achieved remarkable results. The production cycle was shortened by 30%, production speed increased by 25%, dimensional accuracy improved by 15%, surface quality significantly enhanced, and product consistency ensured. Mold manufacturing

costs were reduced by 20%, usage and maintenance costs decreased by 15%, service life extended by 40%, material recyclability increased, and energy consumption reduced. Innovative design has achieved significant results in improving production efficiency, product quality, and reducing costs. Production efficiency has been significantly improved, product quality has been significantly enhanced, costs have been effectively controlled, mold service life has been extended, and environmental friendliness has been significantly improved. However, there are also some shortcomings in innovative design, such as high initial investment costs, high technical barriers, and low acceptance of new technologies by some customers, which requires strengthened market promotion. (Ho, C. M. B., Mishra, A., Hu, K., An, J., Kim, Y. J., & Yoon, Y. J., 2017)

6. Challenges and Development Trends of Innovative Design of Precision Jigs and Molds

6.1 Challenges Faced

The innovative design of precision jigs and molds faces numerous challenges. First, the limitations of high-precision machining and manufacturing technologies are a key issue. Current machining equipment and technologies may not meet extreme precision requirements in certain special cases, such as the manufacturing of micro-nano structures that require sub-micron or even nano-level precision. This poses extremely high demands on the performance and stability of machining equipment. Additionally, high-precision machining equipment is costly, limiting its widespread application in small and medium-sized enterprises.

Second, the development and application of new materials are challenging. New materials are a crucial factor in enhancing the performance of precision jigs and molds, but their development requires significant time and financial investment, with complex processes and low success rates. Moreover, the application of new materials needs to address compatibility issues with existing machining processes and ensure the stability of material supply.

Third, the simulation analysis and verification technologies for complex structural designs need improvement. As product shapes and functions become increasingly complex, the design of precision jigs and molds also becomes more complex, requiring advanced simulation analysis and verification technologies to ensure their performance and reliability. However, current simulation analysis technologies still have certain limitations in handling complex physical field coupling problems, and verification technologies struggle to fully simulate actual working conditions.

Furthermore, the rapid changes in market demand and the trend towards personalized customization pose higher requirements for the design and manufacturing of precision jigs and molds. Companies need to be able to quickly respond to market changes and provide personalized products and services. This not only demands more flexible and efficient design and manufacturing processes but also requires companies to have strong supply chain management and collaborative innovation capabilities.

Lastly, the protection of intellectual property rights and the confidentiality of technology are of vital importance. Innovative design often involves a company's core technologies and trade secrets, and any leakage can result in significant economic losses. However, the legal environment and enforcement of intellectual property protection vary across different countries and regions, and it is challenging to ensure foolproof technical confidentiality measures.

6.2 Development Trends

Despite the numerous challenges, the innovative design of precision jigs and molds is showing positive development trends. The rapid development of intelligent and automated technologies brings new opportunities for innovative design. By introducing artificial intelligence, machine learning, and automated manufacturing technologies, the design process can be intelligent and the manufacturing process can be automated. For example, intelligent design systems can automatically generate optimized design solutions based on input parameters, and automated manufacturing equipment can accurately perform complex machining tasks.

The application of green design concepts in the innovative design of precision jigs and molds is becoming increasingly widespread. With the growing global emphasis on environmental protection, companies are beginning to adopt recyclable materials, energy-saving machining processes, and environmentally friendly surface treatment technologies to reduce environmental impact. For example, using biodegradable materials to manufacture molds can not only reduce waste but also lower energy consumption during the production process.

The multidisciplinary integration of innovative design models will become mainstream. The innovative design of precision jigs and molds requires the comprehensive application of knowledge from multiple disciplines such as material science, mechanics, thermodynamics, and computer science. Through interdisciplinary cooperation, the advantages of each discipline can be fully utilized to achieve design goals for complex structures and high-performance requirements.

The trend of combining personalized customization with mass production is becoming increasingly evident.

Companies can achieve personalized customization on the basis of mass production through technologies such as modular design and flexible manufacturing systems. For example, using 3D printing technology to manufacture personalized product components, which are then assembled with standardized components.

Finally, the strengthening of international cooperation and exchange is promoting the rapid dissemination and sharing of technology. In the context of globalization, international cooperation and exchange in the precision jigs and molds industry are becoming more frequent. Through international cooperation, companies can obtain advanced technologies and management experience to enhance their innovation capabilities. At the same time, the rapid dissemination and sharing of technology also help to promote technological progress in the entire industry.

7. Conclusions and Future Outlook

7.1 Research Conclusions

The innovative design of precision jigs and molds is an indispensable part of modern manufacturing. Through systematic research on innovative design theories and methods, we have summarized a series of effective design strategies, including topology optimization design, biomimetic design, intelligent design, and multidisciplinary integration design. These methods not only improve the precision and efficiency of design but also significantly enhance product performance and quality.

In practical applications, innovative design has shown significant advantages. For example, by optimizing structural layout and adopting new materials, the machining precision and service life of precision jigs have been significantly improved. In mold design, the introduction of hot runner technology and optimized cooling systems has not only shortened the molding cycle but also improved product quality. The application of innovative design has not only improved production efficiency but also reduced production costs and enhanced the company's market competitiveness.

Innovative design is of great significance for promoting industry development. It meets the challenges of complex product shapes and high-performance requirements and adapts to the needs of customized production. By introducing intelligent and automated technologies, innovative design provides strong momentum for the upgrading of manufacturing.

7.2 Future Outlook

In the future, the innovative design of precision jigs and molds will continue to develop in the directions of intelligence, automation, and greening. Intelligent design will be deeply integrated with manufacturing technology to realize the fully automated process from design to production. Green design concepts will be further promoted, prompting companies to adopt more recyclable materials and energy-saving processes.

To further promote industry development, efforts can be made from the following perspectives:

- Strengthen multidisciplinary research to promote the integration of material science, mechanics, computer science, and other disciplines.
- Deepen intelligent design technology by developing more efficient artificial intelligence algorithms and automated manufacturing systems.
- Explore the combination of personalized customization and mass production to improve production flexibility and efficiency.

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