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Research on the Improvement of CNC Machine Tool Machining Accuracy and Tool Optimization Strategies

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Abstract

In the wave of the digital transformation of the manufacturing industry, CNC machine tools have gradually replaced traditional machine tools with their many advantages. However, the domestic CNC machine tool industry faces technical bottlenecks, relying on imports for high-end technologies and core components, and there is a gap in machining accuracy compared with international advanced levels. This paper deeply analyzes the factors affecting machining accuracy in terms of machine tools and tools, and proposes accuracy improvement strategies such as optimizing the machine tool body structure and comprehensive error compensation, as well as tool optimization methods such as additive manufacturing of tools, coating technology, and geometric shape optimization.

Keywords

CNC Machine Tools; Machining Accuracy; Influencing Factors; Improvement Strategies; Tool Optimization.

1. Introduction

Traditional manufacturing technology is undergoing a transformation and upgrading towards digital manufacturing at a rapid pace. CNC machining technology is widely used in the manufacturing industry due to its high processing efficiency. CNC machine tools can use unmanned equipment to complete data processing and production, and have obvious advantages in terms of accuracy, work efficiency, automation level, and product quality. However, there are many factors affecting the machining accuracy of CNC machine tools. Enterprises should focus on researching these influencing factors and proposing solutions to ensure the operation quality of CNC machine tools.

2. Analysis of the Current Machining Situation of CNC Machine Tools

With the manufacturing industry's requirements for high-quality and high-efficiency processing, traditional machine tools will gradually be phased out due to their low processing efficiency and insufficient processing accuracy. The main development direction of the manufacturing industry in the future is to combine CNC machine tools with CNC programming design. Especially for products with large individual differences and low universality, such as precision molds and small parts, more advanced technology is needed to ensure product quality. Compared with traditional machine tools, CNC machine tools have higher manufacturing accuracy and can meet the requirements of complex product manufacturing. In addition, traditional machine tools are restricted by factors such as personnel, machinery and equipment, and actual operation levels, resulting in large differences in the quality of manufactured products, and sometimes even unable to meet subsequent use requirements. By standardizing the parameters in the production process using numerical control technology, the interference of manual operations on work steps can be avoided, the probability of quality problems

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in the mold production and processing process can be effectively reduced, and the product quality can be effectively improved.

At present, most of the CNC equipment produced by domestic machine tool manufacturers and the CNC machining technology they master are at the medium-low end. For example, the processing technology is not sophisticated enough, there are no standardized processing documents, the process cannot be decomposed and transformed into CNC programs, and CNC equipment cannot achieve complete production automation, etc. [1]. High-end CNC technology and core components are almost monopolized by foreign countries. There is a significant gap between domestic CNC machine tools and international advanced levels in key performance indicators such as machining accuracy. Machining accuracy, as the core element to measure the machining quality of CNC machine tools, directly affects the performance and reliability of products and restricts the high-end development of China's manufacturing industry. Both the accuracy control ability of the CNC system and the manufacturing quality of core components are closely related to machining accuracy. In-depth analysis of the influencing factors of CNC machine tool machining accuracy is of great significance for breaking through technical bottlenecks, enhancing the competitiveness of domestic CNC equipment, and realizing the independent control of high-end manufacturing.

3. Analysis of Influencing Factors of CNC Machine Tool Machining Accuracy

3.1 Influence of Machine Tool Factors on Machining Accuracy

The servo system of a CNC machine tool is mainly responsible for the stable operation of the CNC machine tool. Through the operation of the servo system, it provides mechanical power and plays a coordinated control function, directly affecting the errors during the machine tool operation and the machining accuracy. In addition to providing power and coordinated control, the response speed and stability of the servo system also affect the machining accuracy. A slow response speed will lead to processing lags, making it impossible to ensure the precise positioning and movement trajectory of the machine tool. In addition, if the servo system itself has poor stability, it is more likely to cause irregular fluctuations of the machine tool [2].

Many operations of CNC machine tools are carried out on the guide rails. If there is a position deviation or an imperfect fit when the tool is placed on the guide rails, or if the guide rails are worn due to long-term use, guide rail errors will occur, resulting in inaccurate product positioning and further affecting the machining accuracy. In addition, CNC machine tools will generate thermal deformation during long-term operation, resulting in machining errors of the machine tool. This part of the error can even reach 40%.

3.2 Influence of Tool Factors on Machining Accuracy

During the machining process of CNC machine tools, the tool, as a key component directly involved in the cutting work, is the core element for material removal and forming. It contacts the surface of the workpiece with its sharp cutting edge and, driven by the machine tool, rotates at a high speed or moves linearly to gradually remove the excess material, thereby machining the part into the desired shape and size. The rational selection of tools is particularly important for the machining process. Theoretically, a certain tool corresponds to specific processing materials and processing conditions, and the appropriate tool should be selected according to the properties of the processing materials and processing conditions during use. However, in the actual machining process, there is randomness in tool selection, and tools are not used in accordance with relevant technical standards, resulting in situations such as tool sticking, tooth thermal cracking, and tool breakage during the cutting process.

In addition, the structural characteristics of the tool, such as straightness and parallelism, will directly affect the dimensional and geometric tolerances during the machining process. If the structural design is unreasonable, it is easy to cause vibrations and lateral deviations during the machining process, thereby affecting the machining accuracy. Workpieces made of different materials have different requirements for the hardness of the tool. A suitable tool can not only ensure the smooth progress of the machining process but also avoid damage to the tool itself. For example, when machining titanium alloys and special steels, using tools coated with high-wear-resistant coatings can effectively prevent wear and maintain stable machining accuracy [3].

4. Strategies for Improving the Machining Accuracy of CNC Machine Tools

There are many factors affecting the machining accuracy of CNC machine tools. Under the requirements of high-precision machining, corresponding strategies must be proposed for various factors to effectively reduce the error value and improve the accuracy of workpiece production.

4.1 Optimal Design of the Machine Tool Body Structure

The machine tool body structure is the basis for improving machining accuracy. The rigidity and thermal stability of the machine tool material, the smoothness and stability of the transmission system, and the overall structure layout are all the keys to improving machining accuracy. In material selection, machine tool beds made of high-strength cast iron, polymer concrete, and other materials can effectively improve their load-bearing capacity and anti-deformation ability, preventing deformation errors caused by machining. In addition, key functional parts made of low-expansion materials such as ceramics and carbon fibers have less thermal deformation during processing and can maintain dimensional accuracy in different temperature environments. In the design of the transmission system, it is necessary to rationally configure linear axes and rotary axes. For example, the direct-drive technology can be adopted to directly connect the motor to the load, eliminating intermediate transmission components. Core components such as high-precision ball screws and linear guide rails not only need to ensure a pitch error at the micron level but also have high rigidity and long life to ensure the positioning accuracy of the machine tool during high-speed feeding. In the overall machine structure design, it is necessary to consider using high-rigidity structure forms such as trapezoids, cones, and trusses, rationally configure stiffeners, and optimize the guide rail layout, which can greatly improve the overall machine support stiffness and enhance the machine tool's ability to resist external force deformation. Conduct finite-element analysis, simulation optimization, and overall machine topology optimization design on the structure to determine the optimal shape and size of key structural components. Under the premise of ensuring the machine tool performance, reduce the weight of the machine tool, reduce material costs, and further improve the rationality and stability of the machine tool structure. In terms of thermal design, design a reasonable structure to avoid the thermo-mechanical coupling effect, which can prevent the loss of machine tool structure accuracy caused by the mutual influence of thermal deformation and force deformation, and ensure the accuracy stability of the machine tool during long-term processing or high-speed operation. At the same time, a heat conduction module made of high-thermal-conductivity materials can be added between the key heat-generating components and heat-dissipating components of the machine tool to accelerate heat conduction, and cooperate with the internal air duct or liquid-cooling channel of the machine tool to achieve rapid cooling.

4.2 Comprehensive Error Compensation Method

Another effective method to control the machining accuracy of CNC machine tools is comprehensive error compensation. Through the software-hardware system, various errors are identified, calculated using the error compensation mathematical model, and then fed back to the corresponding components for compensation and correction operations. Common errors include geometric errors, errors caused by thermal deformation, and deformation errors caused by cutting forces. For geometric errors, high-precision measuring instruments such as laser interferometers can be used to measure geometric parameters such as the straightness and perpendicularity of the axes, establish a spatial error model, configure error compensation parameters, quantify the geometric errors, and adjust the positions of the moving parts to effectively reduce the impact of geometric errors on machining accuracy. For thermal errors, a machine tool temperature field model is established using finite-element analysis, the temperature information of key temperature-measuring points is collected, and a thermal error compensation model is established for dynamic compensation. At the same time, a

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reliability assessment and a time-series optimization compensation algorithm should be established by comprehensively considering multiple error sources to achieve a more comprehensive evaluation of the thermal error compensation effect and provide support for optimizing the compensation strategy. For cutting-force-induced deformation errors, a model of cutting force-tool deformation-machining error is established. The tool deformation is predicted according to the cutting force, and feed-forward compensation is carried out accordingly [4]. This is of great significance for ensuring product quality, especially in machining scenarios such as high-speed and heavy-load cutting that are sensitive to tool deformation.

5. CNC Tool Optimization Strategies

In the field of modern mechanical processing, high-quality CNC tools are the key elements to ensure machining accuracy and improve processing efficiency. Tool materials should have good bending strength, fracture toughness, and hardness, which can not only effectively improve processing efficiency but also significantly reduce tool wear, and enhance machining accuracy and product quality.

5.1 Additive Manufacturing of Cemented Carbide Tools

In the field of additive manufacturing of cemented carbide tools, there are two common technical routes: Powder bed fusion (PBF) and Forming–debinding–sintering (FDS) technology based on green-body cold printing, debinding, and sintering processes [5]. The PBF technology uses high-energy lasers or electron beams as heat sources to selectively sinter or melt powders. The powders are melted layer by layer and then solidified and stacked to form three-dimensional solid components. For this technical route, more attention needs to be paid to the influence of key parameters such as powder preparation, printing path planning, and laser energy control to achieve more refined processing control and reduce adverse phenomena such as decarburization and cobalt evaporation. The FDS technology produces green bodies through cold printing, then removes the binder in the green body through debinding, and finally sinters the green body into three-dimensional solid components with the required density and performance. The selection of binders and the debinding process of the FDS technology route are crucial, which can ensure the integrity of the green body during the debinding process and reduce the occurrence of cracks and pores.

5.2 Tool Coating Technology

Coating wear-resistant coatings on tools can also reduce the consumption of tools when processing highly abrasive materials.TiAlN, TiN, and DLC coatings are commonly used high-performance coatings [6]. The TiN coating itself has a low friction coefficient, which can reduce the friction between the tool and the workpiece and the cutting chips. At the same time, it has good chemical stability and can form a barrier on the tool surface to isolate the tool from the material and prevent corrosion and wear caused by chemical reactions. Adding AI elements to the TiN coating can promote the rapid formation of a dense alumina layer on the coating surface during the cutting process due to high temperatures, further enhancing hardness and chemical stability. The DLC coating has extremely high hardness and a very low friction coefficient, making it especially suitable for processing highly abrasive composite materials. When processing carbon fiber-reinforced plastics, it can double the service life of ordinary tungsten carbide tools.

5.3 Optimization of Tool Geometric Shape

In addition to methods such as additive manufacturing of tools and coating high-wear-resistant coatings to enhance the wear resistance of tools, setting an appropriate geometric shape can also significantly improve tool performance. By optimizing the tool nose radius, helix angle, and rake angle, etc., the cutting force can be reduced, and the thermal load can be lowered, thereby improving the service life of the tool. Increasing the tool nose radius can improve the strength of the tool nose and also disperse the stress concentration during the cutting process, which plays an important role in controlling the risks of tool deformation and fracture. The helix angle of the tool serves to remove chips, reducing blockages and heat accumulation in the cutting area. Therefore, appropriately increasing the helix angle can ensure the normal progress of the machining process.

6. Conclusion and Prospects

CNC machine tools, with their advantages of high efficiency and high precision machining, occupy an important position in the modern manufacturing industry and are gradually replacing traditional machine tools as the mainstream development direction of the industry. However, with the development of the manufacturing industry towards high-end and sophisticated products, CNC machine tools also need to further enhance their machining accuracy for products to help China's manufacturing industry develop towards the high-end. From the perspective of machine tools, improving machining accuracy can be achieved by optimizing the machine tool body structure and compensating for comprehensive errors using mathematical models. In terms of CNC tool optimization, strategies such as additive manufacturing of cemented carbide tools, tool coating technology, and tool geometric shape optimization can improve the wear resistance and processing performance of tools, thereby ensuring machining accuracy.

Looking to the future, CNC machine tools will further integrate emerging technologies such as big data and artificial intelligence. CNC systems with functions such as intelligent monitoring, adaptive control, and fault diagnosis will be developed to achieve real-time monitoring and optimization of the machining process. The processing technology of CNC tools will also integrate technologies such as the Internet of Things and additive manufacturing to create new productive forces in the industrial transformation and promote the manufacturing industry to develop towards a higher level of intelligence and greenness.

References

[1] Wang Miao, Zhang Zhenming, Li Long, et al. Development status of numerical control technology and its role in intelligent manufacturing [J]. Aeronautical Manufacturing Technology, 2021, 64(10): 20-26. DOI:10.16080/j.issn1671-833x.2021.10.020.

[2] Li Zhanlong. Analysis of influencing factors and solutions for the machining accuracy of CNC machine tools [J]. Digital Agriculture and Intelligent Agricultural Machinery, 2023,(06): 121-123.

[3] Tian Guosheng, Zhou Ting, Zhao Yuewei. Research on the influencing factors of special-purpose tool design on deep-hole machining accuracy [J]. Internal Combustion Engine & Parts, 2024,(24): 73-76. DOI:10.19475/j.cnki.issn1674-957x.2024.24.009.

[4] Lin Ling, Lin Yuhui. Technologies for improving the machining accuracy of CNC machine tools and problem analysis [J]. Die & Mould Manufacture, 2025, 25(02): 157-159. DOI:10.13596/j.cnki.44-1542/th.2025.02.050.

[5] Jiang Feng, Hu Ronghui, Deng Jiedong, et al. Development trends and prospects of additive manufacturing technology for cemented carbide tools [J/OL]. China Mechanical Engineering, 1-23 [2025-04-10]. http://kns.cnki.net/kcms/detail/42.1294.TH.20250324.1613.002.html.

[6] Liang Weijie, Liang Jin. Optimization strategies for tool life in CNC machining of composite materials [J]. Product Reliability Report, 2024,(11): 152-153.