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An Exploration of Multi-Axis CNC Machining Technology in Automotive Component Processing

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Abstract:

With the rapid advancement of the automotive industry, demands for precision and efficiency in automotive component machining continue to rise. As an advanced mechanical manufacturing method, multi-axis CNC machining technology has gained widespread application in automotive component production due to its high precision, efficiency, and flexibility. This paper outlines the fundamental principles and characteristics of multi-axis CNC machining technology, focusing on its application advantages, key technologies, and practical case studies within automotive component manufacturing. It further explores future development trends. Through this research, the aim is to provide the automotive manufacturing sector with practical guidance on applying multi-axis CNC machining technology, thereby advancing the upgrading and development of automotive component processing techniques.

Keywords:

Multi-axis CNC machining technology; Automotive components; Machining precision; Machining efficiency; Five-axis simultaneous machining

1 INTRODUCTION

With societal progress and the vigorous advancement of science and technology, numerical control technology has achieved deep integration with automotive manufacturing, driving improvements in the precision of automotive component machining. Particularly within modern automotive production, the complexity, diversity, and high-precision requirements of automotive components continue to increase, rendering traditional machining techniques increasingly inadequate for meeting demands for efficient, high-quality production. As an advanced machining method, multi-axis CNC machining demonstrates significant application potential in the field of automotive component processing, owing to its high precision, efficiency, and flexibility.

2 INTRODUCTION TO MULTI-AXIS CNC MACHINING TECHNOLOGY

2.1 Definition and Characteristics

Multi-axis CNC machining technology refers to the use of multiple axes on a single machine tool for digital control, enabling the processing of complex workpieces. This technology is typically employed on five-axis or higher CNC machine tools, with some high-end machines achieving nine-axis or greater control capabilities. Characterised by high precision, multi-axis CNC machining facilitates the high-accuracy processing of workpieces with complex geometries. It finds extensive application across sectors including aerospace, medical devices, energy, and automotive manufacturing.

2.2 Fields of application

In terms of application domains, multi-axis CNC machining technology boasts an extensive scope of utilisation. Within the automotive manufacturing sector, it finds application in the high-precision machining of automotive components, engine cylinder blocks, and turbochargers. Within aerospace, the machining of complex components like aircraft engine blades, propellers, and nacelles also necessitates multi-axis CNC machining. Furthermore, this technology plays a vital role in medical devices and energy sectors, including the production of artificial joints, bone pins, dental implants, wind turbine blades, and nuclear power plant components.

3 ADVANTAGES OF MULTI-AXIS CNC MACHINING TECHNOLOGY IN AUTOMOTIVE COMPONENT PRODUCTION

3.1 Excellent capability for machining complex geometries

Compared to manual and conventional control operations, multi-axis CNC machining technology offers significant advantages in the processing of automotive components. Automotive parts often feature complex geometries, particularly for critical components such as engine cylinders, crankshafts, and turbochargers, which present considerable manufacturing and machining challenges. Multi-axis CNC machining excels at processing intricate geometries, accommodating diverse component requirements. For instance, in engine cylinder production, this technology precisely controls the contours of combustion chambers, intake ports, and exhaust ports, enhancing combustion efficiency within the engine cavity. In crankshaft machining, it enables complex surface processing and accurate weight-reduction hole drilling, improving crankshaft balance and service life.

3.2 Enhance machining precision

Multi-axis CNC machining technology is applied in multi-axis CNC machine tools, which possess exceptionally high positioning accuracy, enabling strict control of precision standards in automotive component processing. Through simultaneous control of multiple axes, these machine tools achieve precise regulation of tool movement trajectories, thereby significantly enhancing the machining accuracy of automotive components. This high-precision processing not only ensures component quality but also contributes to extending vehicle service life while improving overall performance and reliability.

3.3 Reduce processing steps

Through the application of multi-axis CNC machining technology, each automotive component can undergo multi-surface machining operations in a single setup during manufacturing and processing. This reduces machining stages, enhances processing efficiency, and elevates the overall production standards of the workshop. Traditional machining methods often necessitate multiple clamping and positioning operations, which can lead to machining errors and increased processing time. Multi-axis CNC machining, however, accomplishes multi-surface machining with a single clamping operation. This effectively eliminates positioning errors and time wastage associated with repeated clamping, thereby enhancing both production efficiency and machining quality.

3.4 Save materials and energy

With the support of multi-axis CNC machining technology, material wastage in automotive component manufacturing and processing has been effectively controlled. Through digitalised management, material application planning has been refined, contributing to enhanced material utilisation efficiency. Concurrently, multi-axis CNC machining enables high-precision processing, thereby reducing material wastage caused by machining errors. Furthermore, the high-efficiency machining capabilities of multi-axis CNC machine tools also help minimise energy consumption, promoting sustainable development within the automotive manufacturing sector.

3.5 Enhance production flexibility

Through programming, multi-axis CNC machining centres can execute diverse machining instructions, facilitating adaptation to the varied production demands of automotive components. This manufacturing flexibility enables the automotive industry to swiftly adjust production schedules and product ranges in response to market fluctuations. For instance, during the development of new vehicle models, multi-axis CNC machining technology can rapidly accommodate design modifications and shifting machining requirements, thereby shortening product development cycles and time-to-market whilst enhancing corporate competitiveness.

3.6 Enhance product competitiveness

Supported by advanced technologies such as multi-axis CNC machining, the automotive manufacturing industry continues to evolve, ensuring the processing quality of its products while continuously enhancing their value-added attributes. Against this backdrop, the competitiveness of automotive products in the marketplace will steadily increase, effectively safeguarding consumer rights. High-quality, high-performance automotive components not only elevate the overall performance and reliability of vehicles but also bolster consumer recognition and loyalty towards automotive brands, thereby strengthening the market competitiveness of automotive products.

4 KEY TECHNOLOGIES IN MULTI-AXIS CNC MACHINING AND THEIR APPLICATION IN AUTOMOTIVE COMPONENT PROCESSING

4.1 Five-axis machining technology

1. Technical Principles and Advantages

Five-axis machining technology represents an advanced CNC processing method, enabling simultaneous control of the tool across five axes to achieve precision machining operations on components. Specifically, the five axes comprise three linear axes (X, Y, Z) for translational movement and two rotary axes (A, B). Under programme control, this ensures greater precision in the tool's motion trajectory. The technology's advantage lies in its capability to machine components of exceptionally complex geometries, such as engine cylinders, crankshafts, and automotive turbochargers.

2. Application Cases in Automotive Component Machining

（1）Engine cylinder machining

In the machining of engine cylinders, operators can utilise five-axis machining centres to precisely control the shape of the cylinder bore. Particular attention must be paid to ensuring programme accuracy during the machining of critical areas such as the combustion chamber, intake duct, and exhaust duct. Effective shape control enhances combustion efficiency within the engine's internal cavities. Cylinder walls also require intricate structures such as fuel injection ports and spark plug holes. The positioning and orientation of these apertures often present significant complexity, necessitating the precision machining capabilities afforded by five-axis machining technology.

（2）Automotive crankshaft machining

During the machining of automotive crankshafts, five-axis machining technology can be employed to achieve complex surface machining and the processing of weight-reduction holes. In complex surface machining, this technology enables the completion of operations on surfaces such as the main journals and connecting rod journals within a single setup, thereby enhancing machining efficiency and precision. For weight-reduction hole machining, this technology precisely forms these holes according to their required shape and position, thereby reducing crankshaft mass and ensuring component balance.

（3）Turbocharger machining

The blades of turbochargers typically feature complex spatial curved surfaces. By enhancing boost efficiency and reducing noise levels, the application of five-axis machining technology ensures precise control over the shape of these blades. Furthermore, the bearing housings of turbochargers also exhibit intricate geometries. To guarantee stable bearing operation, five-axis machining technology is required for the precise machining of these housings.

4.2 Numerical Control Programming and Simulation Technology

1. Numerical Control Programming Technology

Advanced CNC programming software can generate complex machining programmes, which are validated and optimised through simulation technology to enhance the efficiency and safety of automotive component processing. Automated precision machining operations on multi-axis CNC machine tools necessitate the use of software such as CAD/CAM. Technicians employ CAD software to design three-dimensional models of components, subsequently utilising CAM software to generate machining programmes. These programmes are then implemented into multi-axis CNC machine tools to achieve automated precision operations on automotive components. Within CAM software, operators may also directly write G-codes and M-codes to optimise the management of machining programmes for CNC machines. Furthermore, CAM software's automatic programming capabilities can be utilised to generate machining programmes autonomously based on the part's geometry and processing requirements.

2. Simulation and Collision Detection Technology

With the aid of CNC technology, technicians can conduct simulation modelling during the machining of automotive components to detect collisions between cutting tools and fixtures, thereby ensuring the safety of the machining process. Through simulation, tool paths can be optimised, helping to reduce idle travel and enhance machining efficiency. Furthermore, simulation testing enables optimised control of cutting parameters for different tools—such as rational management of cutting speed, feed rate, and cutting depth—to identify optimal parameter combinations for precision machining of automotive components. Taking automotive gearbox machining as an example: during the design phase, CAD software can be employed to create a three-dimensional model of the gearbox housing, achieving precise modelling of internal spatial layout, hole positions, and threading. During the programming phase, the completed CAD model is imported into CAM software for cutting parameter optimisation. The simulation stage involves collision detection, with toolpaths refined according to transmission machining requirements to enhance efficiency and surface finish. In the machining phase, the generated program is transferred to CNC machine tools for execution.

4.3 Error compensation technology

1. Technical Principles

In multi-axis CNC machining of automotive components, errors may arise from systematic deviations and cutting forces. Through error compensation techniques, these discrepancies can be mitigated, thereby reducing their impact on component machining accuracy and enhancing overall processing quality. Specifically, error compensation within multi-axis CNC machining constitutes a method employing software algorithms to rectify deviations arising during actual machining operations. The occurrence of machining errors stems from multiple factors, including inherent manufacturing tolerances of the machine tool itself, thermal deformation, tool wear, and workpiece clamping inaccuracies.

2. Applications in Automotive Component Machining

（1）Machine Tool Error Compensation

Through error compensation software provided by machine tool manufacturers, linear errors, rotational errors, thermal deformation errors and other factors are compensated for, thereby enhancing the machine tool's overall machining accuracy. Particularly when machining automotive components with stringent precision requirements, the application of machine tool error compensation technology can significantly improve machining accuracy.

（2）Tool wear compensation

During machining operations, cutting tools on machine tools gradually wear down, which can also lead to a decline in the machining accuracy of components. Through error compensation technology, the wear condition of machine tool cutting tools can be monitored, enabling technicians to adjust machining parameters at any time to compensate for machining errors caused by tool wear.

（3）Workpiece clamping error compensation

During workpiece clamping, clamping errors may arise due to imprecise fixtures or workpiece deformation. The application of error compensation technology enables automatic correction of the workpiece during machining by adjusting the machining path, thereby mitigating the impact of clamping errors on machining accuracy.

（4）Dynamic error compensation

During the machining of automotive components, dynamic machining errors may arise due to vibrations and friction occurring in the machine tools. To address this, error compensation technology can be employed to continuously monitor the dynamic response of the machine tools and dynamically adjust machining parameters, thereby ensuring the precision of component machining.

（5）Thermal deformation error compensation

Machine tools are susceptible to temperature fluctuations during machining operations, which can cause thermal deformation of components and result in significant machining errors. Consequently, error compensation technology must be employed to continuously monitor temperature variations within the machine tool, thereby preventing deformation errors from adversely affecting the machining quality of components.

5 PRACTICAL APPLICATIONS OF MULTI-AXIS CNC MACHINING TECHNOLOGY IN AUTOMOTIVE COMPONENT PRODUCTION

5.1 Case Study: Huazhong CNC and Dongfeng Equipment Manufacturing Plant Collaboration

Wuhan Huazhong CNC Co., Ltd. (hereinafter referred to as Huazhong CNC) has joined forces with Dongfeng Equipment Manufacturing Plant to mass-produce high-precision four-axis horizontal machining centres equipped with Huazhong CNC's HNC-818B high-performance CNC system. Tailored to meet the CNC machining demands for critical components of passenger car engines, these centres form a flexible production line successfully deployed at a major domestic automotive manufacturer. This flexible production line for passenger car engines possesses capabilities for high-speed multi-surface milling, boring, drilling, and tapping, making it particularly well-suited for processing cast iron components such as cylinder blocks and cylinder heads. Currently, the high-precision four-axis horizontal machining centres jointly produced by HNC and Dongfeng Equipment Manufacturing Plant have achieved batch production for Complementary production, are operating in excellent condition, and have received favourable feedback from users.

1. Machine Tool Performance Parameters High dynamic performance: Maximum linear axis acceleration of 1g, feed rate of 20m/min, rapid traverse of 60m/min. High machining precision: Positioning accuracy up to 5μm, repeat positioning accuracy up to 3μm, milled hole cylindricity within 10μm (hole diameter 100mm). High-Performance Spindle Configuration: Features an electric spindle with 25kW power and maximum speed of 8000 r/min. Hydraulic Locking Turret: Enhances machining efficiency while maintaining heavy-cutting precision during ø120 peripheral milling operations. Dual control panels: The machining position panel controls machine parameters, programmes, and operations, while the front panel manages workpiece handling. The system automatically loads the current workpiece programme. Tool breakage detection: A servo-driven inspection unit at the front of the overhead tool magazine assesses tool integrity before changes or post-machining, ensuring product quality compliance.
2. CNC System Solutions Primary Functions: The four-axis horizontal machining centres manufactured by Dongfeng Equipment Manufacturing Plant primarily utilise the high-speed, high-precision machining capabilities of the HNC-818B CNC system from Huazhong CNC. These centres feature three-axis and four-axis interpolation capabilities, online tool and workpiece measurement, spatial error compensation and fully closed-loop control functionality, fully open network interfaces compatible with smart production lines (expandable to EtherCAT bus communication protocols), and advanced control features including machining big data collection and monitoring.

5.2 Case Study: Collaboration between Huazhong CNC and Beijing Industrial Research Precision Machinery Co., Ltd.

Huazhong CNC has established a close collaboration with Beijing Gongyan Precision Machinery Co., Ltd. to address the automotive industry's demand for CNC machining of critical engine components. This partnership has resulted in the mass production of the μ2000/630HF precision four-axis horizontal machining centre, equipped with Huazhong CNC's high-end HNC-848C CNC system. Currently, the jointly produced precision four-axis horizontal machining centres have achieved volume sales. Primarily employed for machining high-precision components such as powertrain housings and cylinder blocks, they are well-suited for both multi-variety and high-volume production.

1. Machine Tool Performance Parameters Machine Tool Structure: Features a T-shaped layout with a gantry frame structure. The Z-axis employs dual-drive technology to enhance dynamic rigidity, rapidly suppress

vibrations, and improve machined surface quality. The Y-axis incorporates a weight-balanced headstock design to ensure excellent dynamic performance. The foundation components utilise high-quality cast iron, endowing the machine tool with high rigidity, precision, and superior dynamic characteristics. Working Range: Machine table dimensions 630x630mm, XYZ-axis travel 1000/900/900mm. Spindle Configuration: Spindle speed 8000 r/min, rapid traverse 30m/min, linear axis positioning accuracy 0.006mm, repeatability 0.0035mm, rotary table positioning accuracy 6‘, repeatability 3’.

2. Application Results The µ2000/630HF horizontal machining centre, equipped with the HNC-848C CNC system from Huazhong CNC, has been deployed in batch production at an automotive gear transmission company. It is primarily utilised for the efficient, high-precision machining of medium-to-heavy-duty automotive transmission housing components, meeting the user's processing requirements.

6 CHALLENGES AND COUNTERMEASURES IN THE APPLICATION OF MULTI-AXIS CNC MACHINING TECHNOLOGY FOR AUTOMOTIVE COMPONENT PROCESSING

6.1 Application Challenges

1. Technical Complexity Multi-axis CNC machining technology involves the simultaneous control of multiple axes, resulting in complex processing procedures that demand high technical proficiency from programmers. Furthermore, the commissioning and maintenance of multi-axis CNC machine tools necessitate operation by specialised technical personnel.

2. High Equipment Costs Multi-axis CNC machine tools typically command a premium price, presenting significant financial strain for some small and medium-sized enterprises when considering acquisition. Additionally, maintenance and servicing costs for such equipment remain comparatively substantial.

3. Balancing Machining Efficiency and Precision Within multi-axis CNC machining, achieving a balance between enhancing machining efficiency while maintaining precision presents a key challenge. Excessively high machining speeds may compromise dimensional accuracy, whereas excessively low speeds adversely affect production throughput.

6.2 Countermeasures

1. Enhancing Technical Training Given the complexity of multi-axis CNC machining technology, automotive manufacturers should intensify training for technical personnel to elevate their programming and operational proficiency. Concurrently, external specialists may be engaged to provide technical guidance and training, thereby enhancing overall technical capabilities.

2. Optimising Equipment Configuration Automotive manufacturers should rationally configure multi-axis CNC machine tools according to their production requirements and financial circumstances. Equipment costs may be reduced and utilisation rates improved through leasing or equipment sharing arrangements. Furthermore, collaboration with equipment manufacturers to co-develop multi-axis CNC machines tailored to enterprise requirements should be considered.

3. Develop Efficient Machining Strategies To address the balance between machining efficiency and precision, automotive manufacturers may partner with research institutions to develop high-efficiency machining strategies. Optimising toolpaths, cutting parameters, and machining sequences can enhance both efficiency and accuracy. Simultaneously, simulation technologies can predict and refine machining processes, thereby reducing trial-and-error costs and time.

7 PROSPECTS FOR THE APPLICATION OF MULTI-AXIS CNC MACHINING TECHNOLOGY IN AUTOMOTIVE COMPONENT PROCESSING

7.1 Technological Development Trends

1. Enhanced machining precision As automotive industry demands for component accuracy intensify, multi-axis CNC machining technology will evolve towards greater precision. This encompasses more accurate tool positioning, more stable machine tool control, and more effective error compensation techniques. In the future, multi-axis CNC machining is anticipated to achieve nanometre-level precision, meeting the growing need for higher-accuracy automotive component fabrication.
2. More Complex Machining Tasks As automotive designs continually innovate, multi-axis CNC machining technology will need to handle increasingly complex machining tasks. This encompasses more intricate geometries, smaller machining dimensions, and more precise surface quality requirements. In the future, multi-axis CNC machining technology will continually expand its application scope to meet the diverse machining demands of automotive components.
3. Faster Machining Speeds To enhance production efficiency, multi-axis CNC machining technology will require achieving higher machining speeds. This encompasses more efficient toolpath planning, faster machine tool movements, and optimised cutting parameter settings. In the future, multi-axis CNC machining technology is expected to combine high-speed machining with high efficiency, thereby improving the production efficiency of automotive components.
4. More Intelligent Machining Systems With advancements in artificial intelligence and machine learning, multi-axis CNC machining systems will become increasingly intelligent. This will encompass more sophisticated machining strategies, smarter toolpath optimisation, and greater automation in quality control. Future systems are anticipated to incorporate adaptive machining and intelligent monitoring capabilities, thereby elevating both the machining quality and production efficiency of automotive components.
5. More Environmentally Friendly Machining Processes The automotive manufacturing sector faces environmental and sustainability challenges. Multi-axis CNC machining technology must evolve towards more eco-conscious processes. This entails employing more sustainable tool materials, more efficient coolants, and more energy-efficient machine tool designs. Future advancements will focus on reducing waste emissions and energy consumption during machining, thereby advancing sustainable development within the automotive manufacturing industry.

7.2 Market Prospect Analysis

With the continuous advancement of the automotive industry and consumers' increasing demands for vehicle quality, multi-axis CNC machining technology holds promising prospects for application in automotive component manufacturing. On the one hand, automotive manufacturers will intensify investment and research efforts in multi-axis CNC machining technology to enhance the precision and efficiency of component production. On the other hand, as this technology matures and becomes more widespread, its application will progressively extend to a broader range of automotive component machining. Furthermore, with the continuous expansion of domestic and international automotive markets and intensifying competition, multi-axis CNC machining technology will become a crucial means for manufacturers to bolster product competitiveness and market share.

8 CONCLUSION

Multi-axis CNC machining technology holds significant application value in the processing of automotive components. By introducing the fundamental principles and characteristics of this technology, this paper analyses its application advantages, key technologies, and practical case studies within automotive component manufacturing. Concurrently, it proposes corresponding strategies to address challenges encountered in its implementation, while also outlining future development trends and market prospects. It is foreseeable that in future development, multi-axis CNC machining technology will play an increasingly vital role in the automotive component manufacturing sector, driving the advancement and evolution of the automotive manufacturing industry.

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