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Research on Optimization Strategies for Precision Retainability of Multi-Axis Linked CNC Machining Centers

Linghong Zeng*
Jiangxi Electronic Information Polytechnic College, Nanchang 330096, Jiangxi, China

**Author to whom correspondence should be addressed.*

Abstract: Under the background of high-quality development, modern manufacturing industry has put forward higher requirements for the production efficiency and machining precision of mechanical CNC machining. Taking multi-axis linked CNC machining centers as an example, this paper elaborates on the influencing factors of precision retainability, explores specific precision control and optimization strategies around five aspects: error model construction and identification, mechanical structure design optimization, machining parameter adjustment, condition monitoring and error compensation, and construction of maintenance system. It also verifies the effectiveness of these strategies in engineering practice, providing a reference for reducing precision abnormalities of CNC machining centers and realizing high-efficiency operation and high-precision production of equipment.

Keywords: multi-axis linkage; CNC machining center; precision retainability; error compensation; optimization strategy

1. Introduction

Under the background of building a quality power and a manufacturing power, the level of mechanical design and manufacturing continues to improve, and various industries have increasingly higher requirements for the quality and performance of industrial products, which requires continuous improvement of technologies and processes to improve machining precision[1]. Multi-axis machining is a multi-coordinate linked mechanical processing method based on CNC technology, characterized by strong coordination and high degree of freedom. Multi-axis linked CNC machining centers can synchronously control four or more coordinate axes for linked motion according to specific quality standards, completing precision machining of special-shaped structures, complex curved surfaces and complex parts. They are often used in high-end equipment manufacturing fields such as auto parts, mold manufacturing and aerospace. Compared with ordinary CNC machine tools, they have more complex structures, longer kinematic chains, longer operating conditions and complex and variable machining situations. Affected by factors such as control system drift, thermal deformation and tool wear, the machining precision of CNC machining centers is prone to attenuation, making it difficult to ensure the consistency and reliability of processed parts[2]. At present, many scholars have recognized the importance of precision retention and optimization of CNC machine tools, and carried out research on reliability evaluation, error modeling, error identification and dynamic compensation, providing technical support for improving precision retainability[3]. On this basis, grasping the error control factors from a systematic perspective and constructing targeted optimization strategies are of great significance for improving the comprehensive performance and precision retainability of CNC systems and promoting the development of multi-axis linked CNC machining centers towards higher precision and stability.

2. Analysis of influencing factors on precision retainability of multi-axis linked cnc machining centers

The precision retainability of multi-axis linked CNC machining centers refers to reducing the interference of errors on the machining process and ensuring the stability and reliability of machining precision. The influencing factors run through the entire life cycle of the equipment and are mutually coupled, mainly divided into five categories.

2.1. Mechanical structure errors

Mechanical structure is the foundation of precision retainability. The rationality of its design, the machining and assembly precision of components and the wear state directly determine the initial precision and precision retention ability of the equipment. The kinematic chain of multi-axis linked equipment includes core components such as spindle, guide rail and lead screw. Long-term wear of the lead screw nut pair will increase the gap and produce positioning errors. The straightness, parallelism errors and wear of the guide rail will affect the motion stability[4]. Wear and poor lubrication of spindle bearings will reduce the rotational precision. The indexing and coaxiality errors of the swing head and turntable will amplify machining errors through multi-degree-of-freedom motion [5].

2.2. Thermal deformation errors

Thermal deformation error is the main factor causing precision attenuation, accounting for 40% to 70% of the total error. During the machining process, spindle motor friction, lead screw and guide rail friction, cutting heat conduction and ambient temperature fluctuation will all cause thermal deformation of various parts of the equipment, changing the relative positional relationship and thus producing machining errors[6]. Multi-axis linked equipment has a complex structure, and different parts have different thermal expansion coefficients and heating rates. Thermal deformation presents nonlinear and coupled characteristics, and long-term accumulation will accelerate precision attenuation.

2.3. Process system errors

Process system errors include errors caused by unreasonable tools, fixtures, workpiece clamping and process parameters. Tool wear and insufficient sharpening precision will lead to cutting edge profile errors. Insufficient positioning precision of fixtures and unstable clamping force will cause workpiece clamping deviations, which will be amplified in multi-axis machining. Unreasonable tool feeding process and cutting parameters will aggravate tool wear and equipment loss, affecting precision retainability.

2.4. Control system errors

The control system is the core of precision control. Its control precision, response speed and rationality of parameter settings directly affect the positioning and motion precision of the equipment. Improper setting of position loop and speed loop gains will lead to positioning overshoot and response lag. Defects in interpolation algorithms will cause multi-axis coordinated trajectory errors. During long-term operation, aging of electronic components and electromagnetic interference will lead to drift of control precision, further aggravating precision attenuation.

2.5. Usage and maintenance errors

Irregular operation by operators will cause instantaneous precision attenuation, repeated long-term operation will accelerate mechanical wear, and untimely maintenance will reduce mechanical performance. Ambient temperature fluctuation, excessive humidity, external vibration and other factors will also affect the precision retainability of the equipment. Insufficient technical level of maintenance personnel makes it difficult to detect precision hazards in a timely manner, which will further exacerbate the problem.

3. Optimization strategies for precision retainability of multi-axis linked cnc machining centers

In view of the above influencing factors, a systematic optimization strategy is proposed from the perspective of error compensation and processing to further realize error control, reduce machining precision abnormalities and ensure that the equipment is in high-precision and high-efficiency working conditions.

3.1. Precision foundation optimization based on comprehensive error modeling and identification

Error modeling and identification are the prerequisites for improving CNC precision, which require clarifying the error source, influence level and variation law.

3.1.1. Construction of comprehensive error model

Based on multi-body system theory and error transmission law, an error analysis model is established around the control system, thermal deformation and mechanical mechanism. The kinematic chain of the equipment is split into multiple rigid bodies, and the kinematic relationship is described by homogeneous transformation matrix with error parameters integrated to accurately describe and predict machining errors. In the error prediction link, a polynomial chaos expansion model for the randomness of machine tool errors is constructed to improve the practicality, expansibility and versatility of the model through a structured design[7, 8].

3.1.2. Application of high-precision error identification method

A combination of “static identification + dynamic identification” is adopted to realize accurate identification of various errors. Static identification is aimed at fixed errors such as geometry and installation. High-precision equipment such as laser interferometers and ball bars are used to detect relevant parameters, and the least square method is used to fit data and eliminate noise[9]. Dynamic identification is aimed at dynamic errors such as thermal deformation and cutting load. Infrared thermometers, vibration sensors and other equipment are used to collect real-time data, and machine learning algorithms are combined to realize error identification and prediction. A method based on linear regression theory is adopted to improve identification precision. The combination of the two types of identification comprehensively obtains error parameters to support model verification and update.

3.2. Optimal design of mechanical structure to improve the basic ability of precision retention

In terms of mechanical structure, the focus is on optimizing the spindle system, feed system, bed and frame structure to improve mechanical stiffness, stability and thermal stability, and fundamentally reduce error sources[10].

3.2.1. Optimization of spindle system structure

To solve the problems of spindle rotational precision attenuation and serious thermal deformation, high-precision ceramic bearings are selected to replace traditional rolling bearings to reduce friction, reduce heat generation and improve rotational precision and precision retainability. A symmetrical structure is adopted to reduce the unevenness of thermal deformation and increase spindle stiffness. Improve the oil-air lubrication and special cooling system to control thermal deformation.

A flexible coupling is used to connect the spindle and the motor to reduce the impact of vibration and improve system stability.

3.2.2. Optimization of feed system structure

To solve the problems of lead screw wear and guide rail precision attenuation, high-precision ball screws and guide rails are replaced, and preloading technology is implemented to eliminate gaps and improve positioning precision and stiffness. Linear motor drive is mainly used to reduce the wear of kinematic chain links and improve response level [11][12]. The surface of the guide rail is sprayed with wear-resistant materials, and protective devices are added to reduce wear caused by external pollution. Adjust the counterweight structure to suppress the impact and vibration force caused by inertia.

3.2.3. Optimization of bed and frame structure

In terms of machine tool manufacturing materials, materials with low expansion coefficient, high stiffness and high strength are selected to reduce the possibility of material deformation. A box-type and ribbed design structure is adopted to optimize the bed structure. Reinforcing ribs are installed at key parts to suppress the unevenness of thermal deformation and the decline of spatial position precision[13].

2.3. Regulation of machining process parameters to reduce the impact of process system errors

By optimizing the tool feeding process, cutting parameters, tool and fixture selection, standardizing the machining process, reducing process system errors and delaying precision attenuation.

2.3.1. Optimization of tool feeding process

Spiral and oblique tool feeding are adopted instead of traditional vertical tool feeding to reduce tool feeding impact force and tool wear. According to the workpiece material and tool type, the tool feeding speed and feed rate are reasonably determined to avoid uneven load. Layered tool feeding is used for complex curved surface machining to control cutting depth and reduce heat accumulation and tool wear. Optimize the tool retraction process to avoid collision between the tool and the workpiece.

2.3.2. Optimization of cutting parameters

Orthogonal test and response surface method are adopted to integrate data such as workpiece material, tool type and machining precision, establish a correlation model between cutting parameters and tool wear and machining precision, and obtain the optimal combination of cutting parameters after optimization. For high-strength alloys, low cutting speed, moderate feed rate and back engagement are adopted; for ordinary steel, on the premise of controlling precision, parameters are flexibly improved according to machining conditions to ensure the stability of error control.

2.3.3. Optimal selection of tools and fixtures

Establish a tool and fixture life management system. Prioritize the selection of tools or fixtures made of high wear-resistant and high-strength materials such as cemented carbide and cubic boron nitride. Replace suitable tools according to the machining surface, adjust geometric parameters, and regularly maintain and replace worn tools to improve precision consistency. Optimize the positioning and clamping methods of fixtures. According to the complexity of the processed parts, select corresponding special fixtures, control the clamping force within a reasonable range, pay attention to the detection of fixture positioning status, and avoid deformation or loosening.

2.4. Condition monitoring and dynamic error compensation to real-time suppress precision attenuation

Construct a closed-loop control system of “condition monitoring - error prediction - dynamic compensation” to real-time capture precision status and error changes, and suppress precision attenuation through dynamic compensation.

2.4.1. Construction of multi-dimensional condition monitoring system

Establish a precision retainability monitoring system. Use infrared thermometers, laser interferometers and other equipment to collect data such as vibration, temperature and positioning precision of each system component, and monitor the status of mechanical, thermal, machining and control systems. Establish a data acquisition platform, use filtering and noise reduction algorithms to standardize data, and analyze data with machine learning algorithms to realize precision status evaluation and error prediction. At the same time, for system drift and parameter abnormalities, the monitoring system gives timely early warnings to facilitate timely handling of system stability issues [14].

2.4.2. Application of dynamic error compensation technology

Based on linear regression theory, a combination of software and hardware is adopted to use and convert sensor monitoring data, establish dynamic geometric error and wear error compensation models, and real-time correct positioning errors through compensation algorithms to improve compensation precision. For thermal deformation errors, a combination of temperature monitoring and thermal compensation is used. Data from infrared thermometers are used to establish prediction models and real-time correct thermal deformation errors[4]. A multi-variable compensation algorithm is adopted to realize collaborative compensation of multiple components. For control system errors, a closed-loop compensation mechanism is established to reduce them by optimizing parameters, improving interpolation algorithms and optimizing control strategies to improve the stability of compensation effects.

2.5. Construction of standardized maintenance system to delay precision attenuation speed

Construct a standardized system covering daily maintenance, regular maintenance, fault inspection and precision calibration, standardize processes, improve maintenance quality and delay precision attenuation.

2.5.1. Standardization of daily maintenance

Formulate a daily maintenance system to clarify the responsibilities of operators and maintenance personnel. Operators conduct a comprehensive inspection of the equipment status before starting the machine, preheat the machine after starting, clean chips in a timely manner during machining, clean the equipment after machining and keep records. Maintenance personnel inspect key components such as spindle bearings and guide rails daily, add lubricating oil and fasten loose parts to ensure good lubrication of the equipment.

2.5.2. Institutionalization of regular maintenance

Formulate short-term, medium-term and long-term maintenance systems according to the equipment manual and working conditions. Conduct short-term maintenance on a weekly basis, clean debris, inspect the lubrication and cooling system, and test positioning precision. Conduct medium-term maintenance on a monthly basis, mainly inspect fixture precision, check key components, and replace lubricating oil and filter elements. Conduct long-term maintenance every six months, fully inspect the control system, components and mechanical mechanism, detect and calibrate spatial position precision, and timely handle attenuation problems [15].

2.5.3. Regularization of fault inspection and precision calibration

Establish a fault inspection mechanism, equip professional personnel and equipment to accurately locate faults and carry out rapid maintenance, and fully calibrate precision after maintenance. Establish a regular precision calibration mechanism, regularly calibrate precision with equipment such as laser interferometers, and correct parameters and update compensation models according to error identification results. Strengthen professional training for maintenance personnel to improve their technical level.

3. Verification of application effect of optimization strategies

Taking a five-axis linked CNC machining center of an enterprise as an example, it is usually used for precision instrument machining. After long-term operation, problems such as decreased stability and precision attenuation have occurred, mainly manifested in the decline of spindle rotational precision and feed positioning precision, significant thermal deformation and increased scrap rate. Around the above five aspects, a precision retainability optimization plan is formulated, including error identification by establishing a comprehensive error model, comprehensive inspection of mechanical mechanism problems, replacement and upgrading of mechanical components, adjustment of process parameters, introduction of condition monitoring and dynamic compensation system, and establishment of a normalized maintenance system to control and compensate errors.

After the implementation of the optimization plan for 6 months, the results show that the positioning precision has been improved from ± 0.015mm to ± 0.007mm, and the repeat positioning precision has been improved from ± 0.010mm to ± 0.004mm; the spindle rotational precision has been improved by more than 45%, and the thermal deformation error has been reduced by more than 55%; the precision attenuation has been controlled within 0.002mm during continuous operation for 3 months, and the design precision has been maintained for 6 months; the consistency of machining dimension errors of components has been improved by more than 65%, the scrap rate has been reduced from 8.5% to less than 1.2%, and the production efficiency has been improved by 30%. It reflects that the systematic optimization plan has an inhibitory effect on error control and precision attenuation, and has feasibility and engineering application value.

4. Conclusion

In summary, the precision retainability of multi-axis linked CNC machining centers is complex, and the mutual coupling of various error factors leads to precision attenuation. Therefore, relevant personnel should comply with the high-end and high-precision development trend of the manufacturing industry, integrate multi-system and polynomial chaos expansion theory, construct comprehensive error models, formulate optimization strategies for specific error types; optimize the design of machine tool system mechanisms to improve overall thermal stability and mechanical stiffness; optimize relevant process parameters such as tools and fixtures to improve error control level; construct a CNC machining center condition monitoring system, adopt dynamic error compensation technology to effectively suppress precision attenuation; establish a standardized maintenance system to slow down the speed of precision attenuation, extend equipment service life and meet the development needs of the future high-end intelligent manufacturing industry.

Disclosure statement

The author declares no conflict of interest.

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