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Analysis of Tool Wear Condition Monitoring Based on Digital Twin Technology

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Abstract: This paper focuses on the key issues of tool wear condition monitoring in the field of machining, and deeply discusses the application of digital twin technology in this aspect. This paper expounds the principle and architecture of digital twin technology, analyzes its specific methods in tool wear data acquisition, modeling, simulation, and real-time monitoring, and shows the significant advantages of this technology in improving the accuracy of tool wear monitoring and realizing predictive maintenance. At the same time, the challenges faced by digital twin technology in tool wear condition monitoring are discussed, and the corresponding development direction is put forward, aiming to provide theoretical reference and practical guidance for optimizing tool management by digital twin technology in the machining industry.

Keywords: Digital twin technology; Tool wear; Condition monitoring; Machining; Predictive maintenance

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1. Introduction

As an emerging technology of multi-disciplinary integration and multi-technology intersection, digital twin technology can bring new technical ideas for tool wear condition monitoring by creating a digital twin model of a physical entity to map and virtually simulate the physical entity [1]. Tool wear condition monitoring, based on the technology of digital twin, helps tool wear condition monitoring precision and real time, timely finds tool condition, reasonable planning tool maintenance, reduces the enterprise cost, improves enterprise efficiency, thus carrying out tool wear condition monitoring analysis based on the technology of digital twin has important theoretical significance and practical value [2].

2. Based on the number of twin technology principle and method of tool wear condition monitoring

2.1. Tool wear data acquisition

The acquisition of tool wear condition information is the premise for realizing tool wear state monitoring through digital twin technology. In addition to conventional force sensors, temperature sensors, and vibration sensors, image sensors can also be used to collect tool surface image information [3]. The force sensor can measure the size of the cutting force and its variation, and the abnormal variation of the cutting force is very likely to be related to the degree of tool wear. The temperature sensor can measure the temperature of the cutting area, and the cutting temperature will rise after tool wear. The vibration sensor collects the tool vibration information, and the vibration characteristics of the tool will change when the tool is worn. An image sensor through a photograph of the surface of the tool, using the image processing analysis method to collect changes in the morphology, size, and other information. The above sensor information is transmitted to the data layer in real time through the transport layer for processing.

2.2. Construction of tool digital twin model

The key to realizing the digital twin of the tool is to establish the digital twin model of the tool [4]. The specific process is as follows: Firstly, the 3D model of the tool is designed through the 3D modeling software, and the shape, size, and structure of the tool are modeled in 3D. Secondly, according to the theory of material mechanics, heat transfer and other knowledge of the tool for mechanical modeling and thermal modeling, describing the mechanical information of the tool stress, deformation and other mechanical information, while describing the internal temperature field information of the tool, that is, the cutting process of the tool internal temperature changes were modeled. In the tool digital twin model, the collected tool wear information needs to be used as the input to correct and optimize the model, until the tool digital twin model can effectively reflect the current actual state of the tool [5].

2.3. Simulation and analysis of tool wear condition

Use tool digital twin model, simulation analysis tool wear process, by changing the model parameters to the simulation analysis under different conditions of cutting tool wear state, through the results of simulation analysis tool wear mechanism and influence factors, such as the rate of tool wear, cutting tool material performance and the influence of the relationship between the wear and tear. And to compare the simulation results with the actual data, further verify the digital twin correctness and reliability of the model.

2.4. Real-time monitoring and early warning of tool wear status

Through the digital twin model and real-time collected information, the real-time monitoring of tool wear is completed. The collected data into digital twin model, model according to the set of computational algorithms and rules, calculation tool wear and tear on the current and residual life; When the wear degree of the tool reaches the preset threshold or the residual life value of the tool is less than a certain threshold, the system automatically sends out an alarm signal to remind the operator to replace the tool or adjust the processing parameters of the tool in time, so as to avoid processing quality problems or equipment failures caused by excessive tool wear [6].

3. Advantages of tool wear condition monitoring based on digital twin technology

3.1. Improve the accuracy of monitoring

Multi-data dimensions are fused in the multi-source monitoring information to accurately model tool wear, and the turning force signal is obtained through the force sensor. Because the cutting edge area increases after the tool edge wears, the cutting force will change during the cutting process. The temperature data in the turning process was obtained by the temperature sensor. The friction heat generation phenomenon increased due to tool wear, and the temperature increased abnormally. The image sensor obtains the image of the tool surface topography when the tool is worn, and the abnormal phenomenon, such as the area of the surface wear area and the change of the crack diffusion trend, are obtained by the image recognition method. The fused monitoring data are processed with the tool digital twin model to identify the actual wear change, which can reduce the monitoring error to less than 5%, which is much higher than the traditional monitoring method [7].

3.2. Achieve predictive maintenance

Tool remaining useful life prediction based on digital twin method. Taking milling processing as an example, according to the remaining useful life of the tool predicted by the digital twin simulation model during the service period of the tool, the tool wear historical database and in-service monitoring information are integrated to establish the tool wear prediction model through the machine learning method, and the predictive maintenance is realized, so as to avoid the production pause caused by the sudden failure of the tool. To improve the enterprise's production schedule and resource allocation, and improve enterprise efficiency and economic benefits.

3.3. Optimize the processing technology

Based on the digital twin technology, the virtual body model of the tool and the machining process is established, and the influence of various machining parameter combinations on tool wear and machining effect can be simulated. In the drilling process, the digital twin model is used to simulate the tool wear speed, cutting force variation, and hole processing accuracy of the tool under different processing parameter combinations. Enterprises can select the processing parameters to ensure the processing quality and improve the service life of the tool according to the simulated processing results.

3.4. Support remote monitoring and management

Digital twin technology can be combined with network communication technology to cross the geographical restrictions, and remote monitoring and management of tool wear status. By creating a digital twin platform, operators can know the running status, wear status, and life of the tool in real time through computers or mobile phones and other terminals, no matter where they are. For multinational production enterprises, managers at the headquarters can remotely monitor the status of tools on production lines distributed all over the world, allocate resources in time, and maintain tools uniformly. When there is abnormal wear or fault prediction of the tool, the contact person of the relevant tool will be automatically triggered, so that the corresponding treatment can be made in time.

4. Challenges of tool wear condition monitoring based on digital twin technology

4.1. Data acquisition and processing problems

The tool data generated by the cutting process has the characteristics of multi-source, complexity, and real-time, so how to effectively collect, transmit, and process the tool data is an important issue [8]. First, the format and frequency of data collected by different sensors are not consistent, so it is necessary to unify the data formatting and synchronization processing. Second, the scale of data will lead to the existence of data redundancy and noise, and it is necessary to implement effective data cleaning and feature extraction. In addition, the security and privacy of tool data should not be overlooked, and effective encryption and protection are needed in the process of data transmission and data storage.

4.2. The difficulty of model construction and optimization

In the process of constructing the tool digital twin model, various factors that affect the tool's performance, such as tool material performance, cutting process parameters, and processing environment, will have a certain impact. However, the tool performance affects each other, which is not completely understood. Tool in actual application, the tool wear and tear also will be affected by the inhomogeneity of the workpiece material, cutting tool, cutting tool installation deviation length measurement deviation, tool rotating accuracy, the spindle assembly deviation and the influence caused by vibration influence factors such as difficult to model accurately, and according to the actual situation to modify tool wear. Now cutting tools, such as the construction of digital twin model and model parameter optimization method, are not perfect, lacking mature tool standard performance modeling and model updating optimization algorithm, for cutting tool building and application of digital twin model has brought great difficulty [9].

4.3. Problems of system integration and collaboration

The tool condition monitoring system based on digital twin technology needs to be integrated with the production management system and CNC machine control system of the enterprise to realize data sharing and collaborative work. However, the data interface of each system is not uniform, and the communication protocol is not compatible, and the system is difficult to complete the integration work. In addition, the modules in each system in the digital twin system also need to carry out efficient collaborative work, such as how to share data and connect processes between the data acquisition module, model calculation module and application display module in the digital twin system, otherwise it is not conducive to the stability and monitoring effect of the digital twin system [10].

4.4. Shortage of professional talents

Because digital twin technology involves many disciplines and cross fields, high requirements are put forward for talents, who not only master the knowledge of machining and tool technology, but also have the knowledge of computer science and data analysis. This leads to a lack of professional talents who master digital twin technology in China, and the training of talents related to digital twin technology in enterprises and universities is not enough. It cannot meet the practical application needs of digital twin technology, which affects the promotion and application of digital twin technology in monitoring tool wear state and other related fields to a certain extent [11].

5. Development direction of tool wear condition monitoring based on digital twin technology

5.1. Strengthen the research on data acquisition and processing technology

First, data acquisition, breakthrough sensor technology, research and development of high sensitivity, high precision, miniaturization, and other intelligent sensors, such as the use of MEM technology design and production of cutting force sensor, cutting force sensor volume can be as small as 1/10 of the current sensor, and has automatic adjustment function at work, suitable for processing environment, can perceive the subtle changes in the force of the tool. It can reliably and accurately collect data on the small force of the tool. At the same time, it has developed an integrated composite sensor that integrates temperature, vibration, and stress monitoring in one, reducing the number of installed sensors and reducing the cost and complexity of data acquisition. The second is data processing; artificial intelligence is used to overcome the obstacles in data processing. In the aspect of image sensor data, a convolutional neural network can be used to process the data collected by the tool surface image sensor, automatically extract and analyze the tool surface crack, spalling, and other features of the tool surface in the small force area of the tool. In the aspect of sensor data with strong timing, it can be processed by a long short-term memory network, so as to realize the removal of noise data and accurate and timely prediction of the tool wear condition. In terms of data transmission and data storage, the whole process of data communication transmission is ensured, data integrity is guaranteed, and it is not tampered with. The reliability and integrity of network transmission can be guaranteed through blockchain technology, and distributed database technology can facilitate the storage of massive data and improve the efficiency of data resource utilization [12].

5.2. Improve the construction and optimization method of digital twin model

The model construction needs to deepen the research on the tool wear mechanism, and combine molecular dynamics, finite element, multi-scale, and multi-physical field coupling to construct a multi-scale and multi-physical field coupled digital twin model. For example, the influence of atomic interaction on tool material properties and wear on the micro scale; The impact of environmental factors such as cutting force and cutting temperature on the overall performance of the tool on the macro scale, and the coupling of different scale models to improve accuracy. Artificial neural network technology is used to realize the automatic optimization of the model. Reinforcement learning was used to optimize the model structure and parameters by constantly trying different model parameter Settings and machining conditions in the virtual scene, and the reward mechanism was used to guide the optimization of the model structure and parameters, so that the model structure and parameters were better in line with the actual tool wear law. Transfer learning is used to quickly generalize the tool wear model in one machining scene to another similar scene, which greatly reduces the model training time and saves the model training cost. A unified digital twin model construction standard and specification is established, a model library is constructed, and a model parameter library is established to enhance the versatility and reusability of the model, and promote model sharing and collaboration between different enterprises and different systems [13].

5.3. Promote system integration and collaborative development

System integration should unify data interface specifications and communication protocols. According to the standards of Industrial Internet Consortium (IIC) and OPCUA, a unified interface was designed to realize the seamless docking of digital twin system with Enterprise Resource Planning System (ERP), Manufacturing Execution System (MES), and numerical control machine tool control system, which could enable the seamless connection and free flow and sharing of data across systems. Cloud-edge collaboration supports system performance. The tool wear related data analysis task with high real-time performance and extremely fast response to data requirements is placed on the edge side, and the data is processed and judged and responded quickly in the edge computing device at the edge side, such as tool failure warning in advance, and the calculation and analysis tasks with complex model algorithms and long data storage are transferred to the cloud. Make full use of the large computing power and large storage characteristics of cloud computers. Through the introduction of digital threads, information interaction and collaboration can be completed between all links in all stages of the tool life cycle, so as to provide enterprises with complete and accurate information of the system to help enterprises make decisions [14].

5.4. Increase the training of professional talents

On the one hand, colleges and universities should improve the professional course system, add digital twin technology related courses in mechanical engineering and intelligent manufacturing majors, such as digital twin modeling and simulation, intelligent sensing and data processing, etc., and pay attention to practical links, and actively connect with enterprises to form practice and training bases, so that students can participate in specific project practice and improve practical ability. On the other hand, a perfect training mechanism is formed within the enterprise, training is often arranged, employees are allowed to participate in training courses related to digital twin technology, and industry experts are invited to teach and guide. Let employees participate in industry-university-research cooperation projects, and jointly develop technology research and development with universities and research and development institutions. In the practical process of the project, gradually increase experience and realize the precipitation of knowledge. In addition, the government can also introduce relevant policy documents to encourage enterprises to cooperate with universities to carry out talent training. For example, by setting up special scholarships and research funds, more excellent talents can be attracted to engage in the application research work of digital twin technology in the field of tool wear monitoring, and do a good job in talent security [15].

6. Conclusion

In a word, the application of digital twin technology in tool wear state monitoring can not only provide efficient and safe monitoring means for the machining industry, but also optimize the machining process and reduce production costs. However, it should be noted that there are still many problems and challenges in the practical application process of digital twin technology, including talent shortage, data acquisition, and model construction. In the future, it is necessary to strengthen the exploration of related technical means to help this technology be more widely used in the field of machining, and promote the development of the machining industry in the direction of more intelligent and digital.

Disclosure statement

The author declares no conflict of interest.

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