Experiment and Analysis of Thermal Error of Boring-Milling Center Spindle

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Abstract. Taking the spindle of the boring-milling machining center as the research object, analyzes the heat source of the spindle, and uses FILR infrared camera and API spindle analyzer measurement system to design a thermal error experimental detection scheme for the spindle system. The temperature field and thermal deformation of the spindle system. Understanding and grasping the thermal deformation of the spindle system under different operating conditions during operation provides basic data support for the optimization design and compensation of the spindle system.

Keywords: Boring-milling center spindle, Spindle, Thermal error detection, Temperature field, Thermal deformation.

1. Introduction

The study found that during the processing of various high-speed and precision machine tools, the error caused by thermal deformation is as high as 40-70%, which has become the main source of error that affects the accuracy of part processing. The thermal error of the spindle system is one of the main error sources of the machine tool. In order to reduce the errors and ensure the machining quality of the workpiece, effective measures must be taken to study the spindle thermal error[1-2].

Hu Weidong [3] of East China Jiaotong University analyzed the steady-state temperature field heat distribution and thermal deformation of the headstock with a finite element method, which provided a basis for thermal error compensation of the headstock. Xinjiang University Mutharif Ahmed [4] constructed a set of temperature field and thermal error measurement system for the spindle system of machining center based on virtual instrument system, and measured the temperature field and various thermal deformations of the spindle system of machining center A finite element model of the temperature field and thermal deformation of the spindle system of the machining center based on I-DEAS was established, and the temperature field and thermal deformation distribution of the spindle system and its calculation results were obtained.

In this paper, the main components of the boring system of the boring and milling machining center are taken as the research object. The main source of the heat of the spindle is analyzed, and the thermal error detection test is designed. Master the actual working conditions of the spindle system during
operation, and provide basic data support for the optimization design and compensation of the spindle system.

2. Analysis of spindle heat source
Affected by the heat source, the temperature of each component of the spindle of the machining center changes, and the temperature field is not uniformly indexed, which causes the position of the tool and the workpiece to be processed to change relatively, which affects the machining accuracy. For the spindle system of this type of CNC machining center, the main factor affecting the machining and positioning errors of the machine tool is the internal heat source, which mainly includes: the main shaft, two diagonal contact ball bearings, coolant, etc., which will cause local deformation of the machine tool structure. This results in certain deviations, which affects part of the performance of the machining center. Comparatively speaking, the displacement caused by the internal heat source is difficult to predict, and it is larger and changes faster than the displacement caused by the external heat source. Under the influence of the internal and external heat sources, the spindle system will generate a dynamic heat exchange process[5-7]. This dynamic process leads to uneven temperature rise of various components, which is the root cause of the thermal deformation of the spindle system.

TX1600G boring and milling machining center boring system adopts a mechanical spindle structure. When the spindle system is idling, the heating of the motor and the reducer is not considered, and the cutting heat is not taken into account. The main heat source is the frictional heat generation of the front and rear bearings.

3. Thermal error experimental detection scheme for spindle system

3.1. Overall spindle acquisition system solution
The main axis thermal error detection system consists of FILR infrared camera, API main axis analyzer and computer. The overall acquisition system solution is that the temperature and thermal errors collected by the FILR temperature camera and API spindle analyzer are directly converted into digital signals recognized by the computer through relevant analysis software, so as to obtain their temperature and thermal error data. Then, the mathematical model of thermal error can be solved by related theories and calculation methods, and the compensation value can be calculated.

![Fig.1 The overall scheme of temperature field and thermal error detection system](image)
3.2. Main shaft temperature field detection scheme

An infrared thermal imager was used to obtain dynamic temperature data images of the entire spindle. First, 22 temperature measurement points were uniformly arranged in a matrix (see Figure 2), and temperature data collection was performed to find the thermally sensitive areas that had the greatest impact on thermal errors. According to the temperature data collected by the thermal imaging camera for comparison, the thermal sensitive points on the main shaft are selected for thermal analysis.

![Fig.2 The spindle temperature points](image)

3.3. Spindle thermal error detection scheme

The thermal deformation of the spindle is measured by 5 groups of API spindle analyzers, and the measuring points of the spindle's standard probe (tool end) XYZ are arranged in three directions, as shown in Figure 3. Two groups of sensors are arranged near the spindle end and away from the spindle end to measure the thermal error (thermal drift, thermal tilt) in the X and Y directions, and one sensor is arranged on the outer end surface of the probe to measure the thermal error in Z direction (thermal elongation). The signal passes the controller, data acquisition card, and the thermal error test software Spindle Measurement System is used to realize the recording on the PC.

![Fig.3 The installation of API spindle thermal deformation analyzer](image)

4. Thermal error experiment of spindle system

4.1. Transient temperature field test results

Through the previous several temperature field measurement experiments, the thermally sensitive areas with the greatest influence on thermal errors were found concentrated at the front bearing, middle and rear bearings of the main shaft. Therefore, the 22 temperature measurement points were reduced to 9 and completed. The distribution of key points is summarized in Table 1. The temperature data was collected to obtain the temperature change curve of the key points in the middle of the front, middle and rear parts of the spindle system of the transient temperature field spindle system.

As shown in the figure 4, the data graph in this article was continuously collected within 4 hours. The spindle system reached thermal equilibrium when the test reached about 1 hour and 40 minutes, and
then the temperature of the spindle temperature decreased. At about 3 hours and 20 minutes, the spindle stops rotating and begins to cool down.

![Graph showing temperature rise contrastive curve of the central spindle at the front, middle, and rear end.]

**Table 1.** Thermal sensitive point distribution on spindle

|                | Front spindle bearing | Central spindle | After the main shaft bearing |
|----------------|-----------------------|-----------------|-----------------------------|
| Upper spindle  | 04                    | 05              | 06                          |
| Central spindle| 01                    | 02              | 03                          |
| Lower spindle  | 07                    | 08              | 09                          |

**4.2. Thermal deformation test result of main shaft**

The thermal deformation test time of the main shaft is 4 hours, the main shaft speed is 3000r/min, and the main shaft is at about 60,000 ($200\text{min} \times 60 \times 5$) points on the horizontal axis in the figure, and the cooling test is started. Fig. 5, Fig. 6 and Fig. 7 show the thermal deformation of the main axis in different directions with time.

![Graph showing horizontal thermal deformation-time curve.]

**Fig.5** Horizontal thermal deformation-time curve

![Graph showing vertical thermal deformation-time curve.]

**Fig.6** Vertical thermal deformation-time curve

![Graph showing axial thermal deformation-time curve of spindle.]

**Fig.7** Axial thermal deformation-time curve of spindle
5. Analysis of results

5.1. Analysis of transient temperature field
From the temperature rise curve, it can be seen that during the 240 minutes of the spindle running at 3000r/min, the temperature value of different positions on the spindle changes parabolically with time. The highest temperature is about 22 ℃, the lowest is about 18 ℃, the temperature difference between the front and back of the spindle at the same time is small, about 1 ℃; the maximum temperature difference of the spindle at different times is close to 6 degrees.

| Spindle operation Time (minutes) | SP 01 | SP 02 | SP 03 | SP 04 | SP 05 | SP 06 | SP 07 | SP 08 | SP 09 |
|---------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0                               | 16.6  | 16.2  | 16.3  | 16.5  | 16.1  | 16.3  | 16.5  | 16.3  | 16.2  |
| 30                              | 17.3  | 17.0  | 17.1  | 17.4  | 17.1  | 17.0  | 17.2  | 17.1  | 17.1  |
| 60                              | 18.7  | 18.2  | 18.8  | 18.7  | 18.2  | 18.8  | 18.6  | 18.3  | 18.7  |
| 90                              | 19.8  | 19.0  | 19.4  | 19.8  | 19.0  | 19.4  | 19.8  | 19.0  | 19.4  |
| 120                             | 21.8  | 21.0  | 21.4  | 21.7  | 20.9  | 21.4  | 21.7  | 20.9  | 21.4  |
| 150                             | 21.2  | 20.0  | 21.0  | 21.2  | 20.0  | 21.0  | 21.2  | 20.0  | 21.0  |
| 180                             | 20.5  | 19.5  | 20.3  | 20.5  | 19.5  | 20.3  | 20.4  | 19.4  | 20.2  |
| 210                             | 19.6  | 19.0  | 19.2  | 19.6  | 19.0  | 19.2  | 19.6  | 19.0  | 19.2  |
| 240                             | 18.8  | 18.2  | 18.6  | 18.9  | 18.3  | 18.6  | 18.8  | 18.2  | 18.7  |

It can be seen from Table 2 that the spindle system has rapid temperature rise and temperature drop, which takes about 100 minutes. The temperature field consistency of the spindle system is good, and the spindle temperature and room temperature do not change much with time. The maximum temperature rise is controlled at 6 ℃. Left and right, the temperature change of the rear bearing is slightly larger than that of the front bearing. Combined with the spindle structure of the machining center, it can be seen from Figure 6 that the temperature rise at the front and rear bearing positions of the spindle is large, indicating that this is the main heat source.

5.2. Thermal Deformation Analysis of Spindle

| Linear displacement (mm) | Proximal | remote | Difference (mm) |
|--------------------------|----------|--------|-----------------|
| X deformation            | 0.0006   | 0.0012 | 0.0006          |
| Y deformation            | 0.0010   | 0.0034 | 0.0024          |
| Z axis extension         | 0.0300   |        |                 |

The axial thermal deformation-time curve of the spindle during the operation of the machining center replicates the trend of the temperature rise curve with time, indicating that the temperature rise of the spindle is the main cause of thermal deformation. Table 3 shows that the maximum thermal elongation in the Z direction reaches 30 μm, which will seriously affect the machining accuracy of the machining center. In the Y direction, the deformation of the proximal end of the main shaft is small and the deformation of the distal end is large; in the X direction, due to the thermal deformation of the main shaft box, the proximal and distal ends of the main shaft move in a small amplitude. It can be concluded
that the error of the spindle of this machining center in actual operation is mainly affected by the axial thermal elongation error caused by temperature rise.

6. Conclusion
This article analyzes the heat source of the spindle, and designs a thermal error experimental detection scheme for the spindle system. The temperature field and thermal deformation of the spindle system are obtained through experiments, and then the change rule is analyzed. It is concluded that the main heat source of the machining center is the position of the front and rear ends of the spindle, and the error of the spindle in actual operation are mainly affected by the axial thermal elongation error caused by temperature rise, which lays the foundation for the subsequent modeling of the thermal error compensation of the spindle of the boring and milling machining center.

Acknowledgments
This work was financially supported by NFSC (61603262,61403071), Liaoning Natural Science Foundation (20180550418), Foundation of i5 Institute of Intelligent Manufacturing, Shenyang Institute of Technology (i5201702).

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