Volumetric error analysis and modelling of CNC internal and external cylindrical grinding machine tool

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Abstract. In order to improve grinding accuracy, it is necessary to analyze and study geometric and thermal errors of NC machine tools. Based on the method of coordinate transformation of multi-body system theory, the error matrix of cutting points is established in workpiece and tool kinematic chains. The coupling relationship between thermal error and geometric error is analyzed, and the comprehensive mathematical model of geometric error and thermal error of CNC internal and external grinder is deduced. The precise machining constraint equation of grinder is established, which lays a theoretical foundation for subsequent error compensation.

1. Introduction

With the continuous development of modern manufacturing technology and the improvement of product quality requirements, the mechanical manufacturing industry is developing rapidly in the direction of high precision, high speed and high efficiency [1-3]. Precision grinding and ultra-precision grinding technology have become the key technologies to achieve success in the industry competition. CNC internal and external grinders are large workpiece grinding machines and grinding centers, which are suitable for mass production [4]. The wide processing range makes this grinder can be used as a flexible grinder with high flexibility and multi-function. As the main tool for processing hole and shaft parts, the grinding quality and accuracy stability of CNC internal and external grinder are very important [5].

Based on the theory of multi-body system, this paper analyses and studies the geometric error and thermal error of CNC internal and external grinder by analysing the coupling relationship between thermal error and geometric error.

2. Structure analysis and error description of CNC internal and external grinding machine tool

Taking CNC internal and external grinding machine as the research object, the three-dimensional structure of the machine tool shown in Fig. 1 can be established by three-dimensional modeling. It can be seen from the figure that this machine tool is a CNC grinder mainly for processing the outer circle, mainly including the main parts of the bed, head frame, chuck, Z guide rail, X guide rail and rotary grinding wheel frame. According to the law of machine tool motion, it can be divided into two branches: the "bed-workpiece" kinematic chain and the "bed-tool" kinematic chain. As shown in Figure 1, 0-1-2 is a "bed-workpiece" kinematic chain, and 0-3-4-5 is a "bed-tool" kinematic chain.
Through analysis, it can be seen that there are mainly one rotating axis (C axis), moving axis X and moving axis Z for CNC internal and external grinding machine. A single object in space has six degrees of freedom, three displacements and three rotations, respectively. Therefore, the machine tool has nine linear displacement errors, nine angular displacement errors, and three vertical errors.

Geometric errors and thermal errors are the main factors affecting the machining accuracy of CNC machine tools. The thermal error of NC machine tool is a function of temperature, which mainly reflects the thermal displacement in X, Y and Z directions. Temperature has little effect on the rotational error of the object, so it is not considered here. Through analysis, it can be seen that the machine tool mainly has the following thermal error parameters.

3. Establishment of kinematics model of CNC internal and external cylindrical grinding machine tool

This NC machine tool is supported by double-deck worktable, and can process cone, groove, inner and outer circle according to the technological requirements. This paper only studies the error analysis of one kind of processing technology, and other processing errors can be deduced from this. In this paper, the error modeling and analysis of the processing of the outer circle is taken as an example.

Assuming that the workpiece coordinate system is \( Q_w = X_wY_wZ_w \), the tool coordinate system is \( O_t = X_tY_tZ_t \), and the machine tool coordinate system is \( O_o = X_oY_oZ_o \). Through the above analysis, \( P \) is the grinding point of the grinding wheel, then the position matrix expression of point \( P \) in the inertial body coordinate system according to the branch of "bed-workpiece" is as follows:

\[
\{ P_w \}_o = [S01]_p[S01]_pe[S01]_se[S12]_p[S12]_pe[S12]_se[r_w]\quad(1)
\]

The position matrix expression of point \( P \) in the inertial body coordinate system according to the branch of "bed-tool" is as follows:

\[
\{ P_t \}_o = [S03]_p[S03]_pe[S03]_se[S34]_p[S34]_pe[S34]_se[S45]_p[S45]_pe[S45]_se(r_t)\quad(2)
\]

Where \( r_w \) the position matrix expression of point \( P \) in workpiece is coordinate system \( O_w = X_wY_wZ_w \), and \( r_t \) is the position matrix expression of point \( P \) in tool coordinate system \( O_t = X_tY_tZ_t \).

In the process of machine tool grinding, the workpiece outline is composed of the relative motion between the grinding wheel and the workpiece. When the grinding wheel goes out of the designed shape trajectory on the workpiece, it must be strictly controlled that the actual motion trajectory of the tool center always coincides with the tool path so as to realize precision grinding, so that the machine tool can be precisely added. The work constraint equation is as follows:

\[
\{ P_w \}_o = \{ P_t \}_o \quad(3)
\]
4. Solution of constraint equation for precision machining

According to the motion characteristics of the corresponding coordinate system of NC machine tools, the transformation matrix between adjacent bodies is established. On the basis of geometric error, thermal error should be added to get the comprehensive error. Thermal errors only consider displacement errors in X, Y and Z directions, which can be reflected in different transformation matrices.

Through the analysis of the motion structure of the machine tool and the setting of the coordinate system and the grinding characteristics of the machine tool, it can be seen that:

\[
\{r_w\} = \{r/2 \quad 0 \quad z \quad 1\} \quad (4)
\]

\[
\{r_t\} = \{-R/2 \quad 0 \quad 0 \quad 1\} \quad (5)
\]

Where R is the radius of workpiece cross section and R is the radius of tool grinding wheel.

By substituting the various formulas into Formula (3) and omitting the unit matrix, the matrix multiplication is solved by using MATLAB and the higher order infinitesimals are eliminated. The results are as follows:

\[
\begin{align*}
x_{w0} &= \delta_x (x) + \varepsilon_{xx0}(t) - Q_x (\varepsilon_x (z) + \varepsilon_y (x) + \varepsilon_x (x)) + x + Q_{x} (\varepsilon_x (x) + \varepsilon_y (z) + \varepsilon_x (z)) + Q_{x} \frac{y}{2} + \delta_y (x) + \varepsilon_{xx0}(t) + z1 (\varepsilon_x (x) + \varepsilon_y (z) + \varepsilon_x (z)) \\
y_{w0} &= \delta_y (x) + \varepsilon_{yy0}(t) + Q_y (\varepsilon_y (z) + \varepsilon_x (x) + \varepsilon_y (x) + \varepsilon_y (z)) + Q_{y} (\varepsilon_y (x) + \varepsilon_x (z)) + Q_{y} \frac{y}{2} + \delta_x (x) + \varepsilon_{yy0}(t) + z1 (\varepsilon_y (z) + \varepsilon_x (x) + \varepsilon_y (x) + \varepsilon_y (z)) \\
z_{w0} &= \delta_z (x) + \varepsilon_{zz0}(t) - Q_z (\varepsilon_x (x) + \varepsilon_y (z) + \varepsilon_x (z)) - z (\varepsilon_x (x) + \varepsilon_y (z) + \varepsilon_x (z)) + Q_{z} (\varepsilon_x (x) + \varepsilon_y (z) + \varepsilon_x (z)) + \frac{Q_{z} \frac{y}{2} + \delta_z (x) + \varepsilon_{zz0}(t) + z1 + z}{2}
\end{align*}
\]

And

\[
\begin{align*}
x_{w0} &= \delta_x (x) + \varepsilon_{xx0}(t) - Q_x (\varepsilon_x (x) + \varepsilon_y (x) + \varepsilon_x (x)) + x + Q_{x} (\varepsilon_x (x) + \varepsilon_y (z) + \varepsilon_x (z)) + Q_{x} \frac{y}{2} + \delta_y (x) + \varepsilon_{xx0}(t) + z1 (\varepsilon_x (x) + \varepsilon_y (z) + \varepsilon_x (z)) \\
y_{w0} &= \delta_y (x) + \varepsilon_{yy0}(t) + Q_y (\varepsilon_y (z) + \varepsilon_x (x) + \varepsilon_y (x) + \varepsilon_y (z)) + Q_{y} (\varepsilon_y (x) + \varepsilon_x (z)) + Q_{y} \frac{y}{2} + \delta_x (x) + \varepsilon_{yy0}(t) + z1 (\varepsilon_y (z) + \varepsilon_x (x) + \varepsilon_y (x) + \varepsilon_y (z)) \\
z_{w0} &= \delta_z (x) + \varepsilon_{zz0}(t) - Q_z (\varepsilon_x (x) + \varepsilon_y (z) + \varepsilon_x (z)) - z (\varepsilon_x (x) + \varepsilon_y (z) + \varepsilon_x (z)) + Q_{z} (\varepsilon_x (x) + \varepsilon_y (z) + \varepsilon_x (z)) + \frac{Q_{z} \frac{y}{2} + \delta_z (x) + \varepsilon_{zz0}(t) + z1 + z}{2}
\end{align*}
\]

In the actual machining process, the actual cutter center point should coincide with the theoretical cutter center point in the workpiece coordinate system at any time, which is the necessary condition to achieve precision machining. The above calculation results are brought into the formula, namely:

\[
\begin{align*}
X_{w0} &= X_{t0} \\
Y_{w0} &= Y_{t0} \\
Z_{w0} &= Z_{t0}
\end{align*}
\]

The constraint equation of precision machining of the CNC grinder can be obtained. When the constraint equation of precision machining is known, only the related parameters are measured and identified, including geometric error and thermal error. Then error parameters are substituted into the established tool path and NC instructions, as well as the mapping relationship between NC instructions and actual tool path to modify NC instructions to achieve the purpose of error compensation.

5. Conclusion

1) Through three-dimensional modeling of CNC internal and external circular composite grinder, its structure is analysed, and the machine tool structure is described by multi-body system theory. The
machine tool is divided into two branches and several parts, and the body reference coordinate system of each moving part is established.

2) By analysing the motion structure of CNC grinding machine, 21 geometric errors and 9 thermal errors (neglecting the influence of thermal errors on the rotation angle) are obtained.

3) Based on the theory of multi-body system, the transformation matrix of relative motion coordinates among the moving parts of the machine is derived. By analysing the characteristics of thermal errors, the coupling relationship between thermal errors and geometric errors is revealed, and the comprehensive error mathematical model of the machine is further established, which lays a foundation for subsequent error compensation.

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