Visually quantifiable test piece for five-axis machine tools thermal effects

Nuodi Huang[a], Yang Zhang[a], Limin Zhu[a]*, Soichi Ibaraki[b]

a State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China

b Graduate School of Advanced Science and Engineering, Hiroshima University, Kagamiyama 1-4-1, Higashi-Hiroshima, 739-8527, Japan

* Corresponding author, email: zhulm@sjtu.edu.cn

Abstract:

Thermal deviation induced by ambient temperature changes and heat generated during machine operations influences the accuracy of machine tools. A thermal test is essential to evaluate the influence of thermal deviation. ISO 230-3 provides displacement sensor-based thermal tests for machine tools. This paper proposes a machining test that enables a user to visually, by the naked eye, observe the integrated thermal influence on the tool trajectory's displacement in the direction normal to the test piece surface from the length of the machined slots. The proposed test consists of the machining of the five surfaces to observe the thermal influence of the tool position with respect to the test piece in X-, Y- and Z-directions, as well as the position of two rotary axes with respect to the tool position. The advantages of the proposed test include that it requires no measuring instrument to quantitatively evaluate the thermal error in all directions. And since the thermal influence is evaluated by observing the position where the cutting tool leaves the test piece surface, where the cutting force is zero, the influence of the cutting force on the test results can be ignored. Thermal influences of a five-axis machine tool during the warm-up cycle are investigated by experiment to validate the feasibility of the proposed method. Results show that 150 min is needed for sufficient warm-up for the selected machine tool if permissible tolerance for thermal deviation is 2.5 um for all the errors.

Keywords:

Thermal deviation, five-axis machine tool, machining test, test piece design, deviation visualization.

1. Introduction

Five-axis machine tools have been widely used in precision manufacturing. Machining accuracy is immediately affected by the positioning error of machine tools. Among the typical error sources, like kinematic errors, thermo-mechanical errors, loads, dynamic forces, motion control systems and so on, up to 75% of the overall geometrical errors of machined workpieces can be induced by the effects of temperatures [1]. Thermal deformations of the machine tools are generally caused by ambient temperature changes, machine operation, cutting process, flow of coolant and so on [2][3].

As a basis to improve the motion accuracy of five-axis machines under thermally induced errors, it is important to predict, measure, analyze and compensate thermal effects. Prediction of thermally induced errors of bearing [4], ball screw [5], spindle [6], as well as the whole machining system [7] by mathematic models has been widely studied. To compensate the thermal errors, neural network [8], multiple linear regression method [9] and many other methods [10][11] have been investigated. To identify the thermal model, measurement of thermally induced position and orientation errors is essential. Measurement schemes presented in literatures can be categorized into non-machining and machining tests.

Researches have been developed to measure thermally induced deviations of machine tools through non-machining approaches. Gebhardt et al. [12] provided the R-Test measurement to investigate the thermal influence on location errors of rotary axes. Analogous thermal R-Tests for rotary axes are adopted in ISO 230-3:2020 [13]. Bitar-Nehme and Mayer [14] identified the thermal deformation of rotary axis by measuring artefact balls with a non-contact R-test device. Xiang et al. [15] identified the location errors of rotary axis by a double ball bar. Liu et al. [16] presented a scheme to optimize the positions of temperature sensors to predict the thermal influence on the tool's position and orientation.

Optical distance measurement devices are widely used for thermal error identification in non-machining approaches. Ibaraki et al. [17] and Mori et al. [18] presented a scheme to measure the thermal influence on two-dimensional trajectories over the entire workspace by a laser tracking interferometer with and without rotary axis movement, respectively. Ibaraki et al. [19] evaluated the influence of thermal errors on rotary axis location errors by a non-contact laser light barrier system, which is often used for tool geometry measurement. Feng et al. [20] utilized a laser interferometer to measure the thermally induced positioning error of linear axis.

Machining test is another efficient strategy to evaluate the positioning error of machine tools under thermal conditions in actual machining operations. Ibaraki and Ota [21] identified thermal errors of a 5-axis machine tool induced by spindle rotation by comparing the geometric deviations of the machined steps on a cubic test piece with and without spindle warm-up operation. Recently, Ibaraki and Okumura [22] proposed a machining test to evaluate the thermal influence on position and orientation errors of the rotary axis average lines of five-axis machine tools. Wiessner et al. [23] developed a machining test for 5-axis machine tools to measure the thermally induced deviations in X-, Y- and Z-directions, two tool axis orientation errors, and material expansion error of the test piece. Ibaraki and Okumura [24] proposed a machining test to evaluate a machine tool's thermal displacement in the tool's axial direction (Z-direction). Recently, ISO TC39/SC2 has been revising ISO 10791-10 [25] to include the thermal machining tests that are the improved versions of [22], [23] and [24].

These machining tests require the measurement of the finished test piece by using a linear displacement sensor such as a dial gauge, or a coordinate measuring machine (CMM). They enable a user to numerically evaluate the influence of the machine's thermal deformation on the finished test piece's geometry. It is, however, difficult to visually observe the thermal influence. To visualize the thermal deformation directly by eyes, OKUMA [26] and Mareš et al. [27] proposed experimental tests by machining square- and circle-based matrixes, respectively. By machining a set of squares/circles in a column with different tool axial positions, the number of squares/circles visible on the machined test piece shows the actual depth of cut, in other words, the machine's thermal displacement in tool axial direction. In these tests, the "resolution," or the observable minimum thermal deformation, is defined by the difference between the nominal depths of two adjacent squares/circles, and is 5 to 10 um in [26] and [27]. To reduce this resolution, a user may have to machine too many squares/circles. Furthermore, they only present machining tests to observe the thermal deformation to tool axial direction.

The objective of this work is to develop a new machining test to visually evaluate the thermal error of 5-axis machine tools induced by warm up operation or ambient temperature change. In Section 2, machine tool configuration and test piece are illustrated. Test procedures for both linear and rotary axes are also introduced. In Section 3, experimental setup, results and analysis are described in detail, to demonstrate the feasibility of the proposed method. In the end, conclusions and contributions of this work are given in Section 4.

2. Identification of thermal errors through machine test

2.1 Considered machine tool configuration

Machining tests to visually evaluate the thermal influence on motion axes (including both linear- and rotary-axes) are developed in this paper. The proposed method can be applied to any configurations of five-axis machine tools. To introduce this method more intuitively, a machine tool with rotary axes on both spindle side and workpiece side is selected, as shown in Fig. 1.

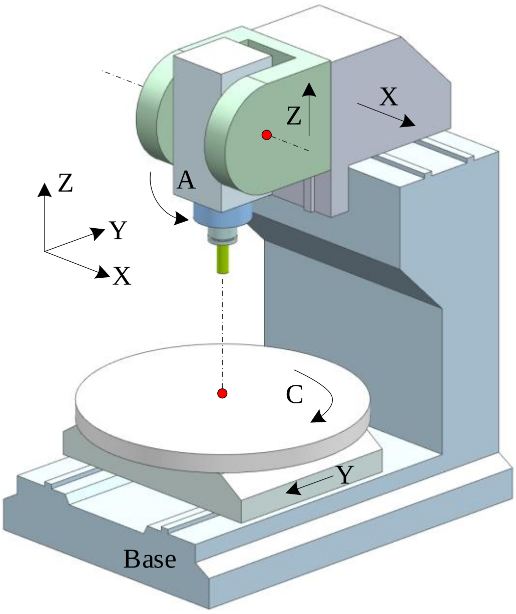


Fig. 1 Five-axis machine tool configuration

2.2 Design of thermal test patterns

Since the thermal deviation causes dimensional changes on micron level, it is difficult to be observed from the workpiece features by the naked eye. In order to quickly evaluate the thermal influence of a five-axis machine tool, a slot is machined by gradually decreasing its axial cutting depth along tool cutting direction, until the tool separates from the workpiece. As shown in Fig. 2, length deviation of two slots under thermal influence, Δy, is

$$\Delta y = \frac{\Delta z}{\tan \alpha} \tag{1}$$

where Δz denotes thermal deviation in z-direction, α denotes the angle between the tool direction and y-direction. In this work, $\tan \alpha$ is set to 0.001. For example, when the thermal error in z-direction is 2.5 μm, the length deviation of the slots is 2.5 mm, which can be observed by the naked eye.

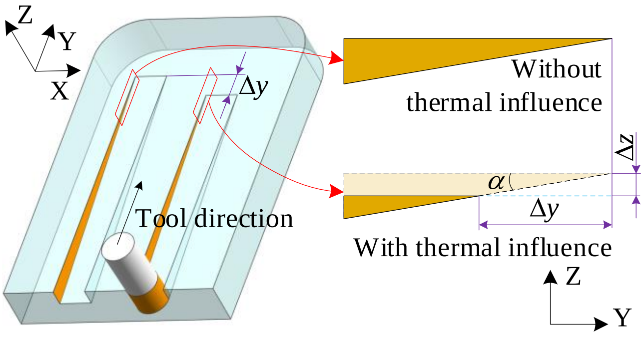


Fig. 2 Visualization of thermal influences

The proposed machining tests are conducted in two phases, which are named as the preparation operation and thermal test operation. In preparation operation, an aluminum alloy stock is clamped on the worktable. To eliminate thermal influence on test piece geometric accuracy, the machine tool needs to be warmed up before machining. In this work, warm-up cycle is defined as controlling the 5 motion axes to move simultaneously at a feedrate of 1200 mm/min for 3 hours, and the accompanied spindle speed is 5000 r/min. Then, the test piece's face for the thermal test operation is face-milled, and the reference slots are machined by using the same tool as the one used in the thermal test operation.

In thermal test operation, a set of test slots are machined under different thermal conditions. If a thermal test is conducted to evaluate the thermal deviation during the warm-up cycle, the machine tool should be shut down after the preparation operation and left to stand for long enough. If it is conducted to evaluate the thermal deviation caused by ambient temperature changes, a warm-up cycle should be conducted in advance to eliminate the thermal influence of warm-up process. To evaluate thermal influence on each motion axis, three different machining patterns are designed. By combining these three patterns, geometry of the test piece for considered machine tool will be designed in Section 3. Note that the proposed patterns cannot be used to identify thermally induced volumetric error component. They are designed to identify thermally induced machining error in X-, Y- and Z-directions and position error of two rotary axes. Thermal error sources are related to the five motion axes, spindle, workbench, stand column, bed etc. For the convenience of description, evaluation of thermal error during the warm-up cycle is considered in this work.

Pattern I: Test to observe thermal influence in X-, Y-, or Z-direction

Machining test to observe thermal influence in X, Y and Z directions are similar. For example, the machining test setup for the Z-direction is shown in Fig. 3. In the preparation operation, a planar surface parallel to x-o-y plane is machined firstly under the full warm-up condition. Then a set of slots are machined by rotating the A-axis to A=45 degrees. To improve geometric accuracy of the test piece and avoid unwanted re-fixture error, the test piece is machined by the same machine tool after warm-up cycle and with little change in ambient temperature. To observe thermal error by the naked eye correctly, scallop height remained by adjacent toolpaths should be small enough. For example, scallop height in this work is 0.015 mm.

Reference slots are used to observe the length change of the line in the machining test. Therefore, they do not have any geometric accuracy requirement if it can be recognized by the naked eye. In this paper, its depth is 0.2 mm. Distance between two adjacent reference slots is set to 2.5 mm. The number of reference slots is 25.

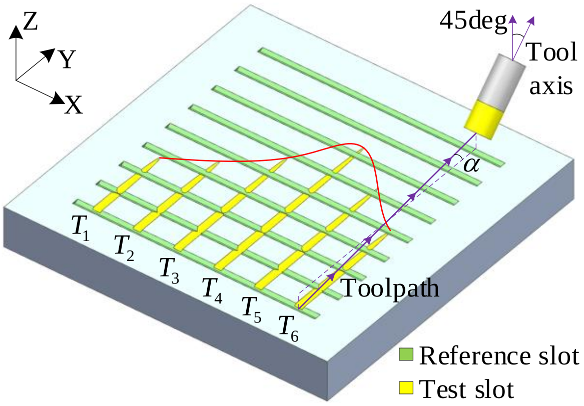


Fig. 3 Machining test setup for thermal influence in Z-direction

In thermal test operation, a set of slots are machined repeatedly with the same time interval. The first slot is machined by feeding a tool to the direction tilted by the angle α from the Y-direction at time T1. In this work, to identify the thermal influence during warm-up cycle, the time interval is 15 minutes. The cutting depth at start point of the toolpath is 0.03 mm. Note that warm-up operation is performed during the prescribed time interval. Then, the second slot is machined in the same way at time T2. This is repeated until the prescribed number of slots is finished. Considering the thermal deviation in z-direction under different temperature environments, length of the slots along the toolpath will change and can be evaluated by counting the number of reference slots they passed. The command tool path is designed such that the cutting tool separates from the test piece surface at the 13th reference slot, if the machine has no error. In reference to the test piece's top surface, the tool's position error in the Z-direction with respect to the test piece's top face is given by:

$$\varepsilon_{Z-axis} = 2.5\left(N_{Z-axis} - 13\right) \tag{2}$$

where N_{i-axis} denotes the number of reference slots that the cutting tool passed. This test shows the Z displacement of the tool relative to the test piece. Note that it is not the real thermal error in Z-axis. It's the combined position error in Z-direction, which are caused by multiple thermal error sources, for example, the thermal influence on the linear positioning error of Z-axis, the change in the Z-position of the table, the straightness error motion of X-axis and many other thermal influences. This work mainly evaluates the influence of thermal errors on the overall accuracy of machine tools.

In some existing machining tests, thermal deviation is evaluated by machining some typical features under different thermal conditions. Cutting force during feature machining may affect the accuracy of the test results. However, in this work, the cutting depth is gradually reduced from 0.03 mm to 0 mm. As the cutting depth decreases, the cutting force will continue to decrease. When the cutting depth is zero, the cutting force disappears. Due to the thermal error, the length of the machined slots is different. One of the advantages of the proposed method is that it avoids the negative influence of cutting force on test results.

Pattern II: Test to observe the position of a rotary axis in the worktable side with respect to the tool

This section presents the C-axis test as an example to show thermal test for rotary axis on worktable side. In preparation operation, a cylinder is machined when the tool axis direction is parallel to z-direction. Then a set of reference slots, parallel to z-direction, are machined at A=45 degrees. Parameters of these slots are the same as the slots in Pattern I. In preparation operation, a cylindrical test piece is rough-machined by milling with the tool axis parallel to Z-direction. The test piece's center axis should be offset from the C-axis centerline. In Fig. 4, the line O represents the C-axis of rotation, and O represents the axis of the test piece. Then a set of reference slots, parallel to Z-direction, are machined at A=45 degrees. In thermal test operation, arcs are machined repeatedly, as shown in Fig. 4. To investigate the thermal influence on C-axis position, it is conducted without moving the tool's position, but by rotating the test piece through the rotation of C-axis. Since the test piece is not coaxial with the C-axis of rotation, the radial depth of cut gradually increases as the C-axis rotates. The test piece's offset should be given such that the cutting depth is d=0.03 mm at the start point of the test toolpath, and the distance from the tool to the workpiece is 0.03 mm at the end of the test toolpath.

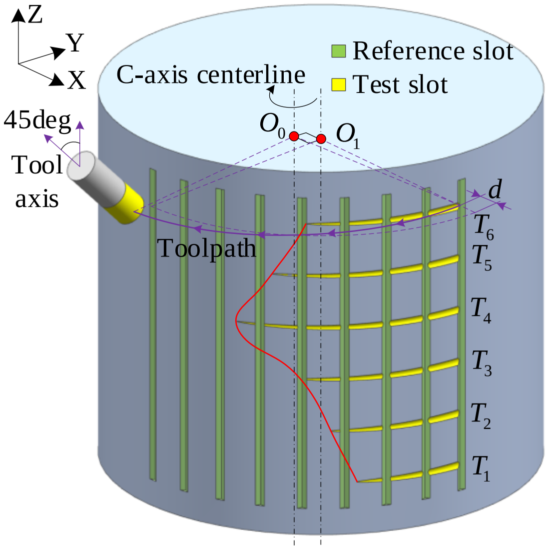


Fig. 4 Test operation for C-axis

The test shows the displacement of the tool in the radial direction of C-axis with respect to the position of C-axis centerline. In other words, it shows the thermal influence on the position of a rotary axis in the worktable side with respect to the tool. The thermal deformation of the machine structure may change both C-axis position and the tool position, and both can influence the test result.

Pattern III: Test to observe the position of a rotary axis in the spindle side with respect to the tool

To test the thermal influence on rotary axis on spindle side, a test pattern for A-axis is designed, as shown in Fig. 5. In preparation operation, an arc surface is machined, whose radius equals to the distance from tool tip point to rotary axis of A-axis. A set of reference slots, parallel to x-direction, are machined at A=0. In thermal test operation, arcs are machined repeatedly, whose radius equals to the distance from tool tip point to rotary axis of A-axis. The arcs are machined by only rotating the A-axis, which can be used to test the thermal influence on A-axis position. Similar to Pattern II, center of the arcs needs to be modified to meet the requirements that the cutting depth is d =0.03 mm at start point of the test toolpath, and distance from the tool to workpiece is 0.03 mm at the end of the toolpath.

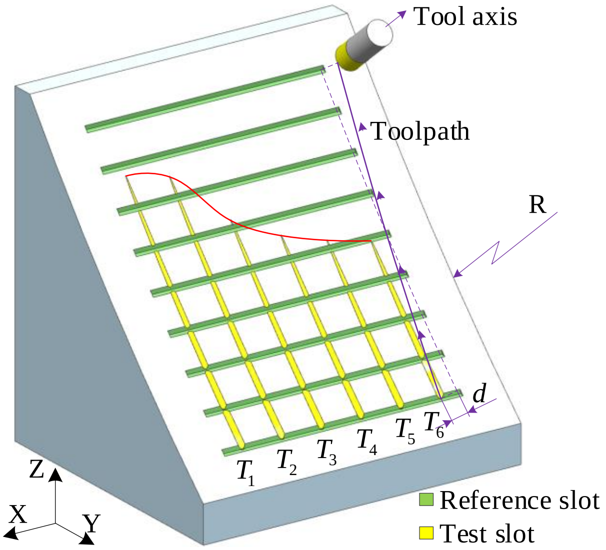
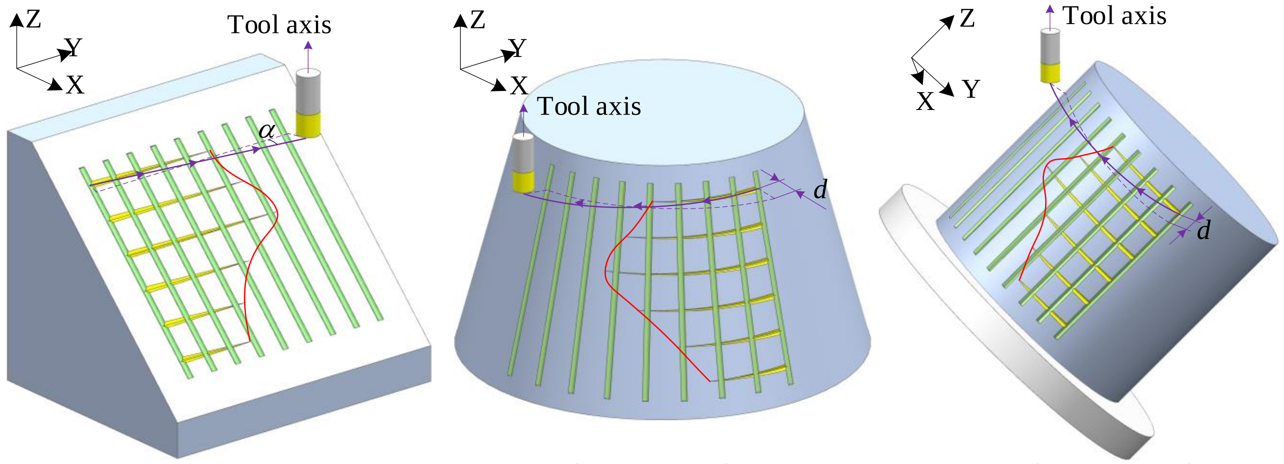


Fig. 5 Test operation for A-axis

2.3 Test procedure for machine tools that do not have a rotary axis in the spindle side

Thermal test method in this paper can be straightforwardly applied to orthogonal five-axis machine tools of any structure, through a simple combination of the developed three test patterns. Note that in Patterns I and II, tool axis direction needs to be tilted by 45 degrees. However, for the machine tools with both rotary axes in the worktable side, it is not possible to tilt tool axis direction directly. To observe the thermal deviation in X- or Y-direction, machine test is conducted on an inclined plane surface, as shown in Fig. 6(a). This test is influenced by the thermal displacements both in X- and Z-directions, but they can be, in principle, separated by additionally performing the test for the thermal displacement in Z-direction. To apply the thermal test for position of C-axis without tool tilt, 2 options are available: substitute the cylinder by a cone, or tilt the C-axis by A (or B) axis, as shown in Fig. 6(b) and 6(c).



(a) Test in Y-direction (b) Test option 1 for position of C-axis (c) Test option 2 for position of C-axis

Fig. 6 Applied to machine tools without rotary axis in spindle side

3. Experimental study on thermal deviation during warm up cycle

3.1 Experimental setup

Based on the thermal test methods developed in Patterns I to III, a test piece is designed to evaluate the thermal deviation of the selected five-axis machine tool, as shown in Fig. 7. The bounding box of the test piece has a size of 120× 150× 80mm. In preparation operation, the machine tool was running continuously by moving the 5 motion axes simultaneously at a feedrate of 1200 mm/min, and rotating the spindle at a speed of 5000 r/min for 3 hours to fully warm-up. There is no special requirement for the toolpath trajectory, but its movement stroke should be as large as possible. Then the workpiece for thermal test was machined by a Φ20 mm bull end milling tool with R2 mm chamfer and 3 cutting edges. The reference slots was machined by a Φ3 mm flat end milling tool with 3 cutting edges. Feedrate and spindle speed are 1200 mm/min and 5000 r/min, respectively. Surfaces and reference slots to conduct the thermal machining test for linear and rotary axes are also illustrated in Fig. 7. Then, the machine tool was stopped for 12 hours to cool down, before the thermal test to evaluate the thermal influences during the warm-up cycle. Note that the distance from tool tip point to rotary axis of A-axis during the machining test is 492.598 mm. Therefore, radius of the arc surface for thermal test of A-axis is the same value.

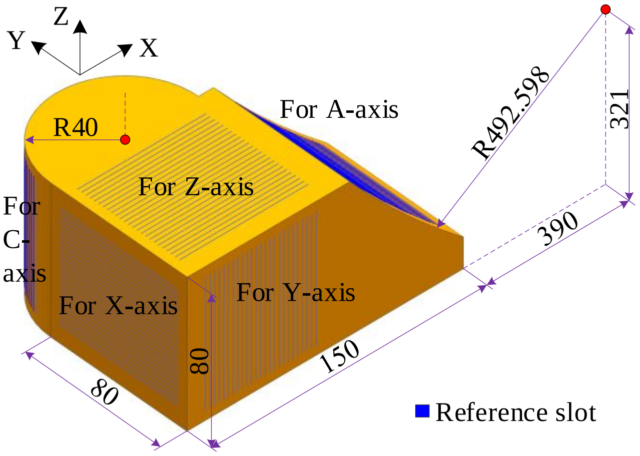


Fig. 7 Geometry of the test piece

The proposed thermal machining test method was conducted on a five-axis machine tool to identify the thermal deviation during warm-up cycle, as shown in 错误!未找到引用源。.

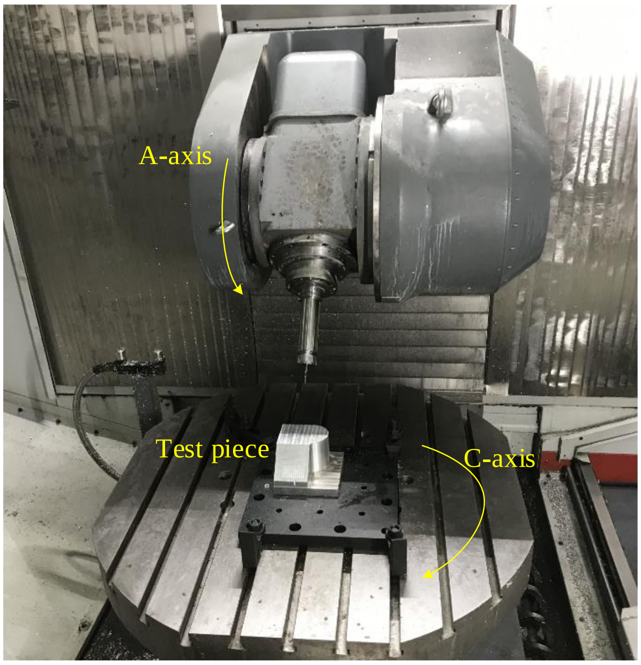
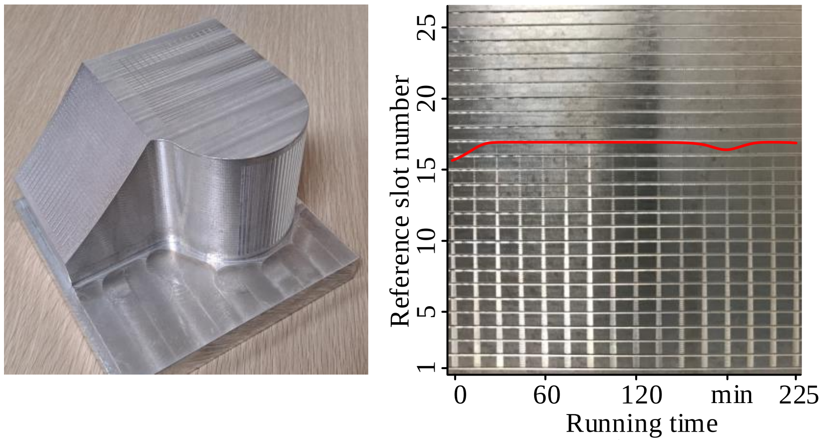


Fig. 8 Selected machine tool and test piece

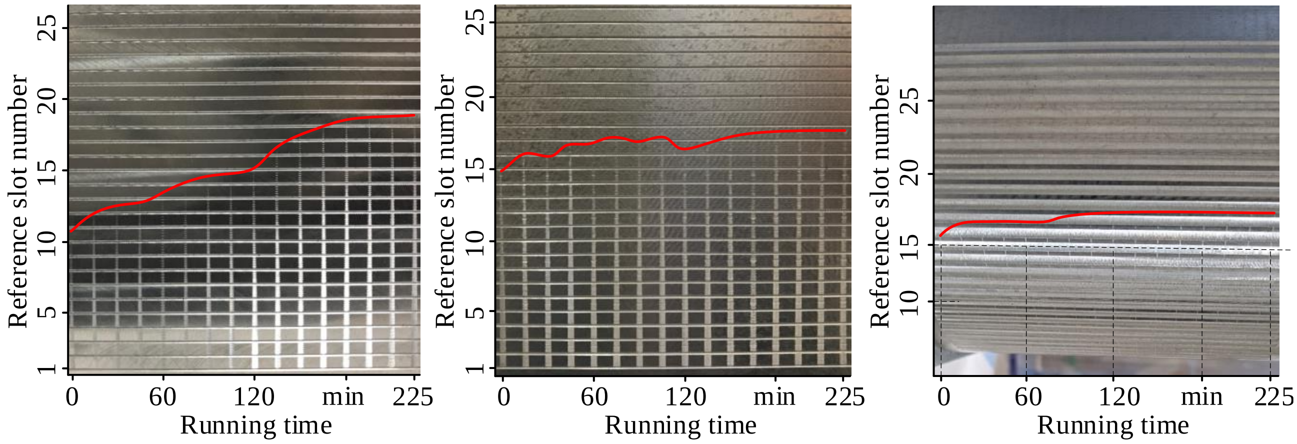
The Φ3 mm flat end milling tool was utilized in thermal test operation. Time interval to evaluate the thermal influence during warm-up operation is 15 minutes. The experiment implementation process is as follows. After the machine tool is turned on, a slot on each of the five faces are immediately machined, which is taken as the initial moment. Machining time is about 1 minute. Distance between two adjacent test slots is 4 mm. Then, warm-up operation are conducted for the rest of time to exercise the 5 motion axes and spindle to produce the warm-up effect. The slot machining and warm-up operation takes a total of 15 minutes. This process is repeated 15 more times to find the relationship between the duration of warm-up time and the thermal deviation.

3.2 Thermal test results during warm up cycle

The machined workpiece and surfaces are shown in Fig. 9. Thermal deviations can be observed by connecting the end point of each slot with a red line. As the warm-up time increases, the change in the machined slot's end position become smaller in all the tests. It can be observed that slots in Fig. 9(c) and Fig. 9(d) are not as clear as slots in other diagrams. This phenomenon is caused by the change of cutting direction. As shown in Fig. 10, when the cutting depth is 0.03 mm, the resulting cutting width is 1.01 mm, if the cutting direction is consistent with the tool tilt direction. If the cutting direction is orthogonal to the tool tilt direction, the resulting cutting width decreased to 0.06 mm. Actually, it can be identified by the naked eye. If no error exists in the machine tool, the test slot should end at the 13th reference line. However, Fig. 9 shows that the machined slot's end position did not converge to this 13th reference slot in all the tests. This phenomenon might be caused by other error sources, like distance error from tool tip point to A-axis, random positioning error, etc. This work is developed to calculate the relative value of thermal deviations.



(a) Machined test piece (b)Thermal test for X-direction (c) Thermal test for Y-direction



(d) Thermal test for Z-direction (e) Thermal test for A-axis position (f) Thermal test for C-axis position

Fig. 9 Thermal deviations during the warm-up cycle

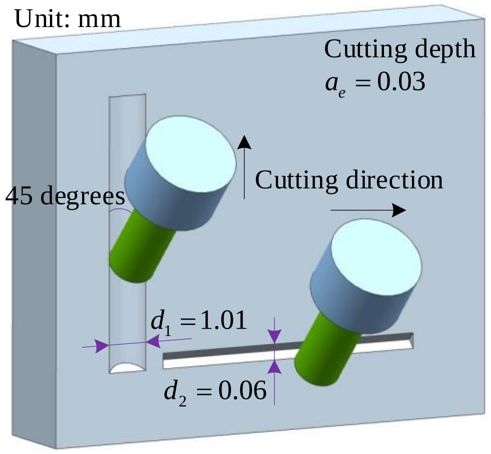


Fig. 10 Change of cutting directions lead to different slot widths

Length of each test slot can be achieved by counting the number of references slot it passes. Thermal error of each axis, that causes the change in the tool trajectory's displacement in the direction normal to the test piece surface, can be calculated by Eq. (2). According to Fig. 9, thermal error can be calculated and shown in Fig. 11. The ambient temperature during the warm-up cycle are also shown in the diagram. The maximum and minimum temperatures during the experiment were 18.1 ℃ and 17.1 ℃. The temperature difference was 1.0 ℃. According to the results, the influence of thermal deviation in X-direction, and position of A- and C-axis were small, compared with the errors in Y- and Z-directions. For example, when the acceptable deviation by thermal influence is 2.5 µm, position of A-axis is fully warmed up after running for 45 min. However, Z- direction needs 150 min to sufficient warm-up. Moreover, thermal error in Z-direction was from -7.5 µm to 12.5 µm, with a deviation of 20 µm. Each direction has different sensitivity to thermal influence, and the required time for sufficient warm-up is also different. In summary, when the acceptable deviation is 2.5 µm for all the errors, the machine tool needs the warm-up operation for 150 min to meet the tolerance.

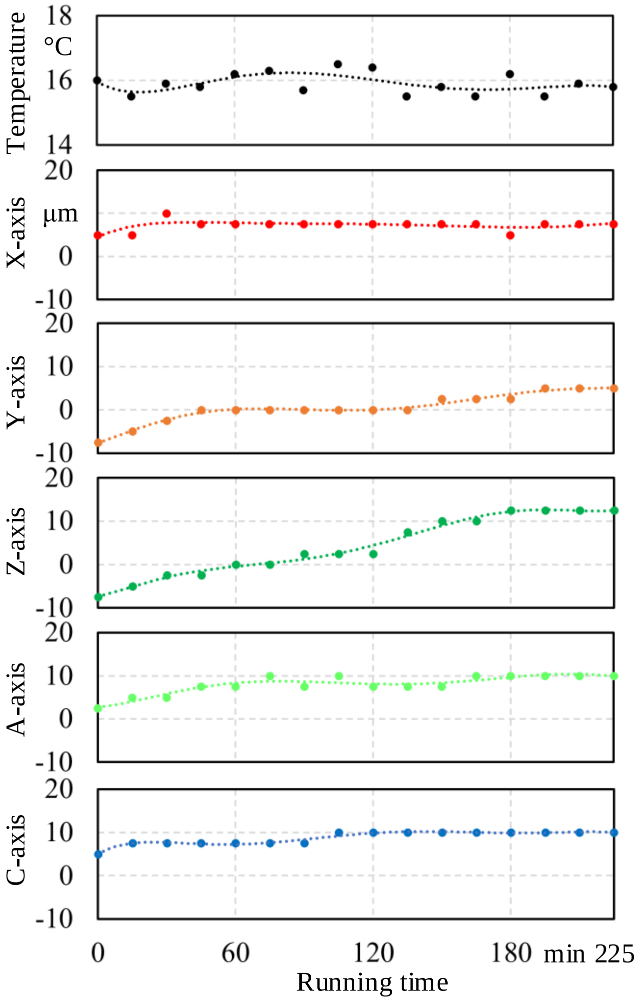


Fig. 11 Ambient temperature and thermal error of each axis

3.3 Machining test results after full warm up operation

In order to prove that the length change of the test slot in Fig. 9 is caused by thermal error rather than other error sources, for example, the geometric error or the repositioning error, an additional machining test is carried out. After the machine tool is fully warmed up, a set of test slots are continuously machined to observe the deviation in Z-direction. Since these two experiments are conducted on different seasons, the ambient temperature for this experiment is 32 ° C.As shown in Fig. 12, distance between the first and last test slots is 40 mm. Results show the deviation in Z-direction is within 2.5 μm, which indicates that when the machining area is small, other error sources have little negative influence on the proposed thermal error evaluation method.

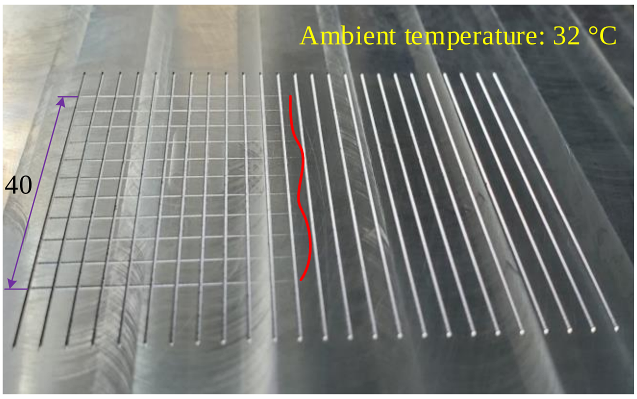


Fig. 12 Machining test after full warm up operation

4. Conclusion

This study proposed a machining test to evaluate the influence of thermal deviation on position errors of the five-axis machine tools. The contributions of this study are summarized as follows.

(1) The test is conducted by machining a set of slots with a linear reduction in cutting depth along the feed direction. The length of these slots is used to evaluate the thermal deviation. Through a set of pre-machined reference slots, the length of the slots can be identified by the naked eye. The proposed test can be evaluated without using any measurement equipment, like a coordinate measurement machine, which makes it easy to implement.

(2) An experimental study is conducted for a five-axis machine tool to evaluate the thermal influence during the warm-up cycle. The present test allows a user to evaluate the thermal influence of the tool position with respect to the test piece in X-, Y- and Z-directions, as well as the position of two rotary axes with respect to the tool position. The results show that 150 min is needed for sufficient warm-up of this machine tool, if the permissible tolerance for the thermal deviation is 2.5 μm for all the errors.

This work provides a scheme to evaluate the influence of thermal error on volumetric error, but cannot be used to identify each thermal error component. In our future work, we will try to develop a methodology to rea-timely identify and compensate the thermal- and geometric-induced volumetric error by utilizing several laser track interferometers simultaneously.

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