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# Validation of thermal errors compensation models for different machine tool structures via test pieces

Otakar Horejš[1], Martin Mareš[1], Lukáš Havlík[2]

[1] Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Production Machines and Equipment, RCMT, Horská 3, 128 00 Prague, Czech Republic
[2] KOVOSVIT MAS Machine Tools, a.s., náměstí T.Bati 419, 391 02, Sezimovo Ústí, Czech

O.Horejs@rcmt.cvut.cz

**Abstract**
Although real-time software compensations of thermal errors exist, the majority of these models are not sufficiently validated in real finishing operations using a test piece. The accuracy and robustness of the developed models are mostly examined using non-cutting measurements. In contrast, machining tests can be more intuitively understood to evaluate the machine's accuracy for typical machine tool users. Moreover, the machined test piece represents a suitable method to verify thoroughly the industrial applicability of the developed thermal errors compensation model for machine tool builders. In addition to that, the test piece can be also employed for the evaluation of machine tool thermal errors, obtaining thermally induced displacements at the tool center point over time. It can be consequently applied as input data for compensation model development. The paper presents the authors' recent research on these issues. Specific test pieces for different machine tool structures are illustrated, e.g., test pieces for validation of thermal error compensation of a gantry-type 5-axis milling centre with a rotary table, a six-spindle automatic lathe and a vertical turning lathe.

Test piece, Machine tool, Thermal error, Compensation, Accuracy, Validation, Machining test, Measurement

## 1. Introduction

Thermally induced errors are dominant sources of machine tools inaccuracy and are often the most difficult types of errors to reduce today [1]. Thermal behavior impact on machining accuracy at the tool center point (TCP) can be recorded by direct or indirect measurements. The direct measurements are based on the requirements of the ISO 230-3 [2], ISO 10791-10 [3], and ISO 13041-8 [4]. The ISO standards describe the experimental procedure and the technical evaluation of the measurement results. The TCP displacements are sensed relatively between the main spindle and the machine table by means of contactless displacement transducers. Indirect measurements with the test piece lead to very illustrative statements about the working accuracy of the machine tool. In contrast to direct measurements, the machine errors and process influences act summarily on the results at the test piece [5].

Software compensation of thermally induced displacements at the TCP is a widely employed technique to reduce thermal errors due to its cost-effectiveness and minimal demand for additional gauges. Although real-time software compensations of thermal errors exist, the majority of these models are not sufficiently validated in real finishing operations using the test piece. The accuracy and robustness of the developed models are mostly examined by means of non-cutting measurements per the international standards mentioned above. It is evidently important to evaluate thermal errors compensation models by such non-cutting measurements, especially during the development of the compensation model. To ensure the high robustness of the compensation model, it is crucial to test the model with a wide spectrum of operating conditions for a long period of time including time-varying environmental temperature influences.

In contrast, machining tests can be more intuitively understood to evaluate the machine's accuracy for typical machine tool users [6]. Moreover, the machined test piece represents a suitable method to verify thoroughly the industrial applicability of the developed thermal errors compensation model for machine tool builders. Thus, test piece machining is an appropriate alternative to the thermal displacement measurement given by international standards [7]. In addition, to carry out direct measurements of thermal errors requires special devices and software. Given the fact that the vast majority of shop floors do not have the possibility to test their machine tools regularly for thermally induced errors with special measuring equipment, there is a high demand for a simplified measurement procedure

To detect position and orientation errors and error motions under machining conditions, test pieces have been developed. Examples of test pieces for NC machine tools are given in ISO 10791-7 [8]. ISO 10791-7 describes machining tests for machining centers, but it only evaluates the geometric accuracy of a single finished test piece and assumes that the machine is thermally stable after sufficient warm-up. There is no international standard specially dedicated for test pieces which are able to capture the machine tools thermal errors, despite the fact that these are crucial for industrial improvements concerning thermal issues on machine tools. Many researchers have proposed machining tests to evaluate a machine tool's geometric accuracy (see a review in [9]), but few have been applied to thermal error evaluation. Current research concentrates on the design of new test pieces which are able to capture the thermal errors of machine tools [10].

In [11], [12] a previous design of a geometrical test piece is extended for the measurement of thermally induced error motions of rotary axes. Three different pyramid-shaped test pieces are manufactured every 25 min to measure thermal effects. The features characterizing the thermal deviations are measured with a touch probe system directly on the machine, under the assumption that the linear axes have small volumetric errors in comparison to the rotary axes. The idea of a compact test piece for the evaluation of the thermally induced translational displacements of the TCP is presented in [5]. The test piece consists of several reference surfaces manufactured at the beginning of the test cycle. The heat input into the system is generated by the rotation of the spindle as well as several axis movements. Thermal test piece for 5-axis machine tools was proposed in [10]. The objective of this paper is to introduce a validation of thermal errors compensation models via different test pieces. Specific test pieces for different machine tool structures are illustrated in the paper.

## 2. Gantry-type 5-axis milling centre with a rotary table

A test piece was machined to verify the industrial applicability of the developed thermal error model in the *Z* axis, see [7]. The tested machine was a gantry-type 5-axis milling centre with a rotary table (diameter 630 mm) and symmetrical structure. The test piece material was an aluminium alloy. The surface was covered with an eloxal coating for better visibility of cutting tool imprints on the surface caused by thermally induced displacements at the TCP. The test piece fixed on the table in the machine tool workspace is depicted in Fig. 1. The flatness of the test piece upper anodized surface is less then 10 µm.

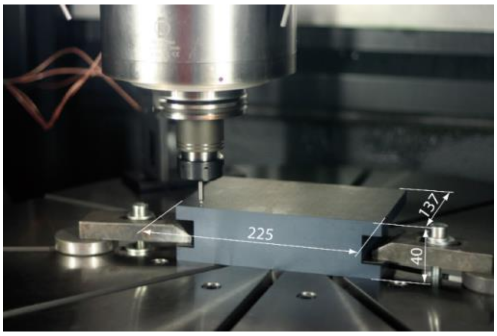


**Figure 1.** Test piece fixed on the table of the gantry-type 5-axis milling centre [7]

The procedure for creation of the test piece is described in Fig. 2. The process was divided into two cyclically repeated phases: machining tool imprints in a column and conducting a test with simultaneous spindle rotation and movements along the *Z* axis (see the specification in Fig. 2). One column of tool imprints was machined with a programmed *Z* tool positioned, as shown on the left side of Fig. 2 (with 10 µm step up to 130 µm). Thereafter, the test with simultaneous spindle rotation and movements in the *Z* axis was carried out (2 hours). The procedure was repeated until the entire matrix of imprints was machined (10 columns; 18 hours), as depicted on the right side of Fig. 2. The complete matrix would have contained only three rows in the ideal case (without any thermally induced displacements at the TCP). This ideal case corresponds to the blue imprints on the right side of Fig. 2. The red imprints reflect a thermal distortion in the *Z*-direction caused by loading periods over time. The vertical scale of the thermal test piece provides a visual imprint of the TCP thermal deformations under the specific test with simultaneous spindle rotation and movements in the *Z* axis (with 10 µm resolution, as mentioned above).

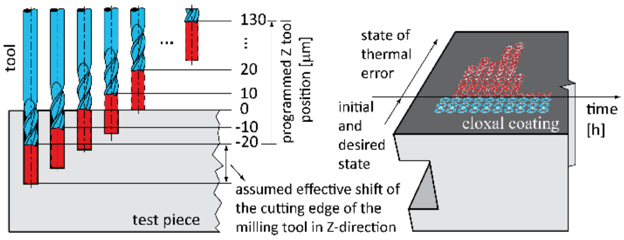


**Figure 2.** Test piece manufacturing procedure [7]

The test piece constitutes a means of comparison between the uncompensated state of the gantry-type 5-axis milling centre and after application of the thermal error model based on transfer functions (TFs), see [7]. A plan view of the manufactured test piece with an imprint of the measured thermal deformations in *Z*-direction is shown in Fig. 3. Reduction of thermal displacements in the *Z*-direction with the aid of the thermal error compensation model using TFs was as high as 92% compared with the uncompensated state (achieved reduction by the model application from 130 µm to 10 µm).

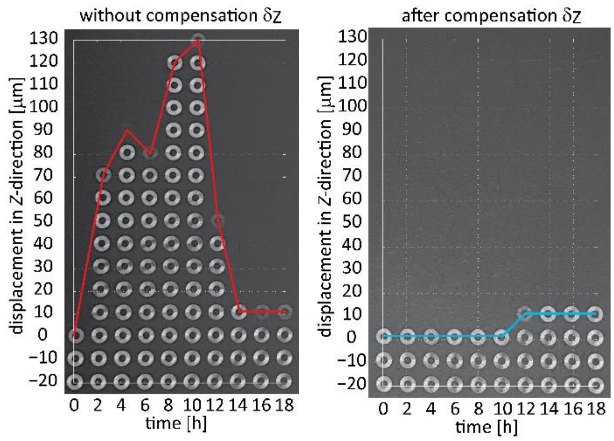


**Figure 3.** Machined test piece without compensation (left) and with thermal error compensation based on TFs (right) [7]

## 3. Six-spindle automatic lathe

The test pieces can be also employed for the evaluation of machine tool thermal errors (obtaining thermally induced displacements at the TCP over time, which can be consequently applied as input data for compensation model development). This application is illustrated on a six-spindle automatic lathe, in particular the MORI-SAY TMZ642CNC numerically controlled six-spindle automatic lathe produced by TAJMAC-ZPS. Workpiece spindle units are arranged around a central axis, which can be driven rotationally and advanced from one machining position (MP) to the next MP. The only critical direction to compensate is the *X*-direction (workpiece diameters that are machined at different MPs of the six-spindle automatic lathe), see [13].

This kind of machine tool is typically used for one workpiece technology in the long term. Thus, to obtain thermally induced displacements at TCP in the *X*-direction is suitable to employ several sets of manufactured steel test pieces. The basic scheme of the test piece, manufactured by a specific technology, is depicted in Fig. 4 (left) [13]. The diameter denominated as $D_1$ (38 mm) of the test piece is manufactured at the first MP, the diameter denominated as $D_2$ (34 mm) of the test piece is manufactured at the second MP, etc. Test pieces were machined only in certain time intervals during the calibration measurement (due to material savings). The time interval was changed according to the actual thermal state of the six-spindle automatic lathe from 5 min (at the beginning of the test) to 30 min (at the end of the test). Since the cutting operations are carried out only during a short period of time to manufacture the test pieces, the influence of tool wear can be neglected.

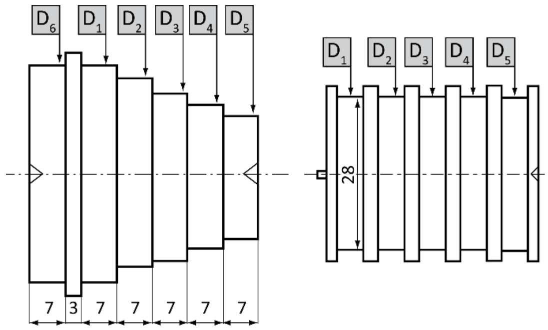


**Figure 4.** Different test pieces for six-spindle automatic lathe [13], [14]

The recording of thermal displacements of the examined diameters ($D_1$ to $D_6$) was obtained by machining the test piece sets in defined time intervals. One set stands for 6 test pieces (one revolution of the spindle drum which lasted 60 s). Thus, several sets of test pieces represent the time axis of the thermal displacements of the machine in the *X*-direction, see Fig. 5.

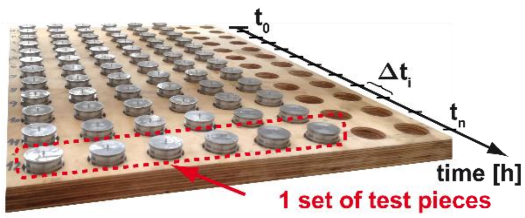


**Figure 5.** Several sets of manufactured test pieces on the six-spindle automatic lathe [14]

Subsequently, the manufactured sets of test pieces were gauged on a coordinate measuring machine (CMM) in an air-conditioned room. Obtained thermal displacements in *X*-direction are applied as input data for thermal error compensation model development. The compensation model which predicts thermal errors in *X*-axis in different MPs of the six-spindle automatic lathe is presented in [13]. The further improvement of the thermal error compensation model via a smart sensor for measuring spindle drum temperature is discussed in [14]. The slightly different test piece was selected for validation of the modified thermal errors compensation model, see Fig. 4 (right).

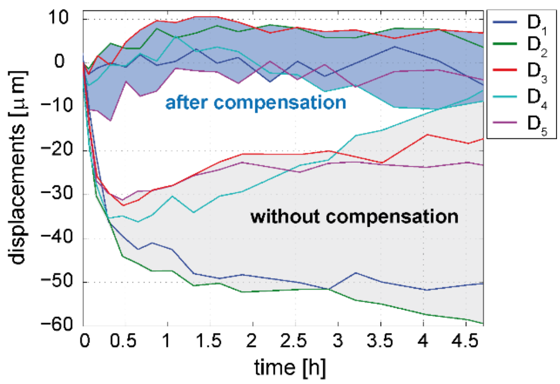


**Figure 6.** The comparison of thermal errors in *X*-axis for six MPs without thermal compensation and after compensation [14]

The changes of the test piece diameters $D_1$ to $D_5$ over time measured by CMM (representing the six-spindle automation lathe thermal errors in *X*-axis in different MPs) manufactured without thermal compensation and after application of compensation are shown in Fig. 6. The light-grey area in Fig. 6 stands for the thermal displacement envelope of the uncompensated state (the maximum thermal displacement in the *X*-direction is -58 µm) and the blue area delineates the envelope of the compensated state [14].

## 4. Vertical turning lathe

Another test piece was machined to validate the thermal errors compensation model of a vertical turning lathe with a rotary table diameter of 3,000 mm. The compensation model predicts linear deformations in *Z*-direction caused by rotary table activity, see [15]. Thermally induced errors caused by rotary table speed are nonlinear and a dependency on the workpiece clamping diameter was taken into account.

The test piece is presented in Fig. 7. The test piece material was grey cast iron. The test piece consists of four circular areas 1 (8), 2 (7), 3 (6) and 4 (5) meant for manufacturing and measuring in *Z*-direction, respectively. The test piece clamping diameter was 1,200 mm and the model gain factor of $g$ = 0.76 had to be adjusted. The test piece was placed on accurately polished underlies (for potential measurement with CMM machine) and fixed to the rotary table by clamps [15].

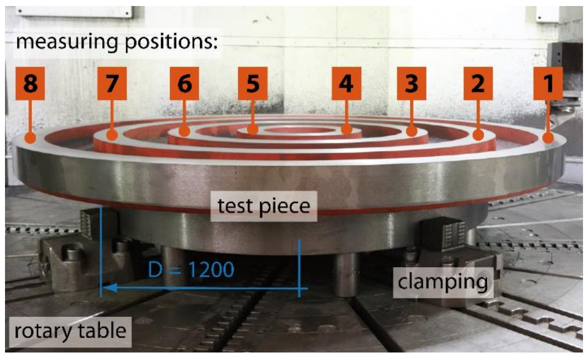


**Figure 7.** Test piece for vertical turning lathe [15]

The manufacturing process of the test piece during the verification test within finishing cutting conditions is depicted in Fig. 8 (left). Measuring principle of manufactured areas is shown in Fig. 8 (right). The combined standard uncertainty of the measurement is 3 µm.

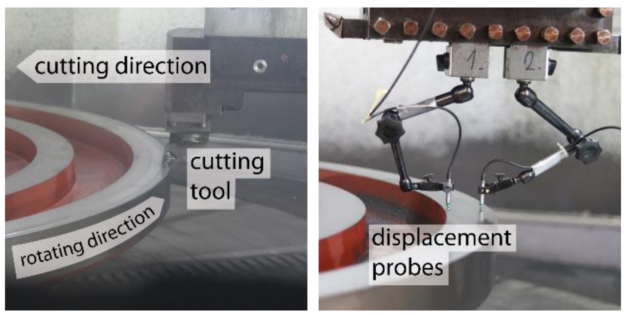


**Figure 8.** Test piece manufacturing (left) and measuring (right) [15]

The test piece manufacturing process was carried out as follows. First circular area 1 (8) was manufactured by prescribed finishing cutting conditions (Table 1). Then the steady cutting tool waited 1.5 hours between areas 1 (8) and 2 (7). Rotary table was active at constant rpm. The second area 2 (7) was manufactured after the pause and so on until the tool reached the middle of the test piece and the experiment was ended.

**Table 1** Cutting parameters during manufacturing of the test piece [15]

| **table speed** [rpm] | **depth of cut** [mm] | **feed rate** [m·min$^{-1}$] | **pitch** [mm·rpm$^{-1}$] |
|---|---|---|---|
| variable (see Fig. 9) | 0.2 | 120 | 0.15 |

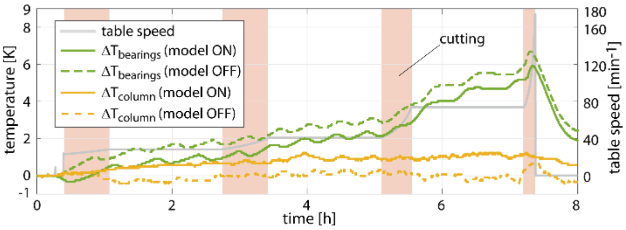


**Figure 9.** Cutting test set-up, conditions and model input behaviours [15]

Two contact displacement probes were mounted on the headstock tool holder to measure the test piece deformations after the vertical turning lathe cooled down (see Fig. 8). The two points were measured in all measuring positions (1 to 8). Table was repositioned five times (in 45°) and all positions measured for statistical data; evaluation uncertainty of Type A.

Two experiments were carried out (with and without thermal error compensation active in the machine tool control system) to evaluate the vertical turning lathe accuracy enhancement. The measured model input behaviours and the table speed during both tests with the cutting process are depicted in Fig. 9.

The arithmetical mean of thermally induced errors in *Z*-direction was calculated from the measured data in all measuring positions. The measured deformations in *Z*-direction with active compensation are depicted in Fig. 10 (left). Deformations without compensation are shown in Fig. 10 (right). Since the experiment set-ups are similar, both machine tool thermo-mechanical states are possible to easily compare.

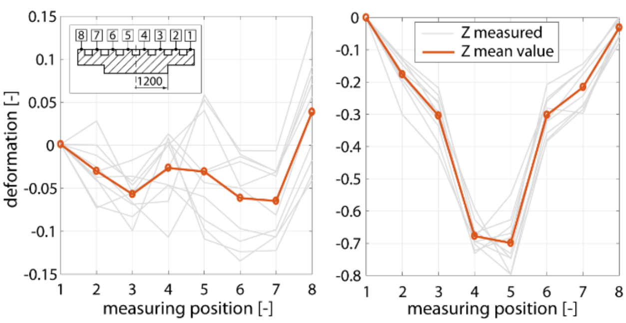


**Figure 10.** Measured deformations with compensation (left) and without compensation (right) during the finishing cutting tests [15]

The improvement of the thermo-mechanical state is estimated 7-fold (87%) in the *Z*-direction compared to the uncompensated state of the vertical turning lathe. Additionally, the test piece thermal errors were measured by a precision level and with CMM machine with similar results.

## 5. Conclusions

The paper presents the authors' recent research on the validation of thermal errors compensation models via test pieces. As there is no international standard specially dedicated for test pieces which are able to capture the machine tools thermal errors, specific test pieces were proposed for different machine tools structures.

Different test pieces are employed due to the fact that the tested machine tools structures have naturally different thermal behaviour. Thus, each of the tested machine tools requires a specific test piece to evaluate thermal errors at the TCP. In addition, it is quite typical that machine tools users often require to manufacture specific test pieces for machine tool acceptance purposes from machine tools manufacturers. Specifically, the test pieces for validation of thermal error compensation based on TFs of the gantry-type 5-axis milling centre with a rotary table, the six-spindle automatic lathe, and the vertical turning lathe are discussed in detail. Manufactured test pieces prove that the developed compensation models based on TFs significantly minimize the thermal errors at the TCP of the tested machine tools. Test pieces are suitable tool for visualization, quantification and evaluation of thermally induced errors of machine tools

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