Measurement of the effect of the cutting fluid on the thermal response of a five-axis machine tool

P. Hernández-Becerro[1], P. Blaser[2], J. Mayr[1], S. Weikert[1], K. Wegener[2]

[1]*inspire AG, Technoparkstrasse 1, 8005 Zürich, Switzerland*

[2]*Institute for Machine Tools and Manufacturing (IWF), ETH Zürich, Leonhardstrasse 21, 8092 Zürich, Switzerland*

Abstract

This paper deals with the influence of the cutting fluid on the thermal behavior of five-axis precision machine tools. The machine under investigation is exposed to several cutting fluid supply modes. The temperatures on the machine surface, of the environment and of the coolant are measured. An electronic level evaluates changes of the inclination along the Z- and Y- axis. To complete this study, an Environmental Variation Error (EVE) test under workshop conditions is carried out. It is observed that the combination of different lubrication modes alters the machine thermal behavior and strongly influences the angular deviations of the axes under investigation.

1 Introduction

Thermo-mechanical errors account for the largest part of the overall errors of manufactured parts, as stated by Mayr et al. [1]. Effective measurement techniques need to be developed in order to evaluate the machine design and compensate the generated thermal errors. The evaluation methodology needs to be able to measure at several locations in the whole working space, as the different axes of the machine have different thermal responses at different positions, modifying the orientation and location of the axes, as explained by Ibaraki et al. [2]. Additionally, the measurement time needs to be as short as possible, in order to capture the different time constants of the thermal behavior of the machine. These metrological requirements pose great challenges.

Standard measurement techniques described in ISO 230-3:2007 [3] focused on the evaluation of errors at single points. The required increase in accuracy of machine tools led to an extensive research of the thermal geometric errors in the whole working volume of machines even with rotary axes. Gebhardt et al. [4] used the R-Test, an indirect volumetric measurement technique developed by Weikert [5], in order to evaluate the thermally induced position and orientation errors. The work focused on the average errors of the rotary and swiveling axes evaluated with a discrete R-Test, without considering how these errors change with position. Gebhardt et al. excluded the influence of the linear axes, which were assumed not to be affected by the thermal loads investigated. Mayr et al. [6] evaluated the average thermal errors of the B-axis with a continuous R-Test procedure, measuring at a frequency of 100 Hz. Ibaraki and Hong [7] used the R-Test to further evaluate the component errors of rotary axes, measuring at 25 different positions of the C- and B-axis with a measurement time of 2 min. Bitar-Nehme et al. [8] measured with a device similar to the R-Test, the Capball, the relative displacement in X-, Y- and Z-direction between the tool and workpiece at different poses of the rotary B- and C-axis. Mayr et al [9] also addressed the measurement of thermal errors with a procedure similar to the static R-Test using a 2.5D touch probe, which enabled fully automated compensation.

Another possibility to measure thermal geometric errors is multilateration techniques, based on laser interferometers with tracking capabilities. Gómez-Acedo et al. [10] employed this technology in combination with electronic levels and temperature sensors. They measured 12 points on the Y-Z-plane with a single tracking interferometer, which was moved to 7 different positions. This approach required a total measurement time of around 30 min. Ibaraki et al. [2] applied the multilateration techniques with a single interferometer to the assessment of thermal geometric errors. The measurement was limited to trajectories on a single plane, provided that the linear position errors were previously measured and the position of the device was calibrated. This way, the measurement time could be significantly reduced. Brecher et al. [11] used four tracking interferometers simultaneously to measure thermally induced deviations. They estimated 17 of the 21 geometrical errors of a three-axis machine tool by measuring 162 points of the working space in 6 min.

Among the different thermal effects to be measured, the influence of cutting fluid has gained importance. Mayr et al. [12] concentrated on the effect of cutting fluid on rotary axis of a five-axis machine tool. The effect of the cutting fluid was demonstrated to have a significant influence on the geometrical errors; suggesting its consideration already in early development stages of machine tools. The work focused on cutting fluid without re-cooling system delivered by flexible nozzles around the spindle head. They neglected the effect of the cutting fluid shower, whose purpose is to remove the chips after the machining process. Pavliček et al. [13] studied the influence of using different cutting fluid media. They compared the thermally induced deviations using oil and CO_2, showing different thermal behaviors of the machine tool for each medium. The thermal errors were evaluated with an in-house developed measurement setup with a special retractable cover to protect the sensors against the fluid.

Machine tools usually deliver the cutting fluid in different ways, which are named cutting fluid supply modes, affecting different part of the structure. The state of the art does not consider how the combination of the cutting fluid supply modes modifies the thermal behavior of the machine. The main contribution of this paper is a presentation of a systematic study of the thermal influence of these different supply modes on the precision of the machine tool. The use of inclination levels is a common method to evaluate the geometric accuracy of the machine tool axes. In this study electronic levels are used in order to assess the thermal geometric errors with a reduced measurement time. Chapter 2 describes the measurement method and is followed by the presentation of the results of both the recorded temperatures and the variation of the inclination in chapter 3. In this chapter, the thermal response with different combinations of cutting fluid supply modes is presented and continued with a study of the effects of the environmental changes. A discussion of the obtained results is carried out in chapter 4, providing also an outlook of the presented research.

2 Measurement procedure

The measurements are performed on a five-axis machine tool with horizontal spindle. The kinematic chain according to ISO 10791-1:2015 [14] is:

H [w B’ X’ b Z Y A (C) t]

The temperature of the machine structure is measured with direct-to-digital temperature sensors attached to the surface. The position of the temperature sensors on the table are displayed in Figure 1. Several sensors are monitoring the unaffected environmental temperatures. These sensors are located at different heights and horizontal positions, in order to capture the spatial variability of the room temperature. In order to further characterize the environmental influences, the temperatures of the workshop floor are recorded, which are considered as a reference temperature value. Also the temperature of the air in the working space is monitored. In Table 1, the specifications of the temperature sensors are listed.

Table 1 Data of the temperature sensors

Sensor	Range	Nominal accuracy	Resolution	Number of sensors	Sampling time
Direct-to-digital temperature sensor	0 to 70 °C	±0.5 °C	0.1 °C	20	11 s
Environmental temperature sensor	0 to 50 °C	±1 °C	0.1 °C	8	60 s

The inclination levels are devices commonly used in industry to measure the inclination and vertical straightness deviations in machine tools. This measurement device is included in the ISO 230-1:2012 [15]. The electronic level measures angular changes with respect to the reference gravitational direction. The electronic level employed in this work is the Talyvel 3, from the manufacturer Taylor Hobson. The specifications of the sensor are summarized in Table 2. In order to evaluate the thermal geometrical errors, the thermal drift should be kept small. During several measurements conducted in the machine, a maximum of 3.0 °C in 12 h is observed, which leads to a zero drift ±0.15% of the measured value. The contribution of this effect to the measurement uncertainty is not considered relevant.

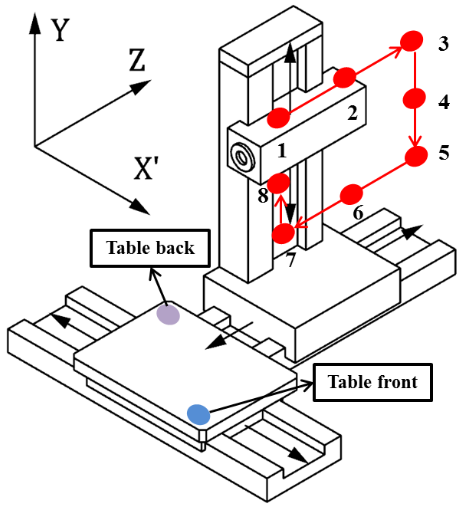

Figure 1 Location of the measurement points of levels from 1 to 8 and location of the temperature sensors. Adapted from ISO 10791-1:2015 [14]

The electronic level is located fixed to the Y-axis. It is positioned outside of the working space to avoid interferences with the cutting fluid during operation. During the measurement with the electronic level, only the Z-axis or only the Y-axis is moved at a time. This enables the separate evaluation of the straightness errors associated to the Y-axis and those associated to the Z-axis. The measurement is done at 8 points homogenously distributed along the full range of the considered axes, forming a rectangle in the Y-Z-plane, as depicted in Figure 1. This way, 6 measured inclination values are associated to the Y-axis and 6 to the Z-axis. The measurements show similar results evaluating the inclination of the Z-axis at the two different positions of the Y-axis; therefore only measurements from point 5 to 7 are going to be evaluated. This also happens for the Y-axis, where the points from 3 to 5 are chosen for further evaluation. One interesting way to evaluate the results is to calculate how the inclination varies from one point to the other, which is associated with the curvature of the axis. The difference of the inclination from point 5 to 6 of Z-axis is named “Inclination back Z-axis” while the difference from 6 to 7 is named “Inclination front Z-axis”. The difference of the inclination from point 3 to 4 of Z-axis is named “Inclination Y-axis up” while the difference from 4 to 5 is named “Inclination Y-axis bottom”. At the beginning of the measurement the values are set to zero, as the main interest is the relative variation of the inclination with time.

As the main objective of this study is to measure the effect of the cutting fluid, the speed of the axes is kept low in order to introduce just the minimum amount of heat possible from the drives. After reaching every measurement point a waiting time is programmed to cancel out all dynamic effects.

Table 2 Data of the electronic level

Sensor	Range	Nominal accuracy	Thermal drift of zero	Resolution
Talyvel 3	±3 mm/m	±1 μm/m or ±2% reading	±0.05% of reading per °C	1 μm/m

The machine under investigation has three supply modes to provide cutting fluid. An external system can provide pressurized fluid to the working space through the spindle head, named Head Cutting Fluid (HCF). The fluidic media can also be delivered by a shower over the working space, named Shower Cutting Fluid (SCF). Finally, the fluid can be inserted at the back of the Z-axis flowing along the axis and bed into the working space; this supply mode is named Bed Cutting Fluid (BCF). The HCF and the SCF affect homogenously the whole working space. The BCF enters the working space from the part of the Z-axis further from the working space, affecting this area in an inhomogeneous manner. The temperature of the fluid is controlled by an external unit before entering the machine. The control temperature is set to vary with the measured reference temperature, which represents the environmental variations.

During operation, a combination of different cutting fluid supply modes is usually used. The measurements are therefore organized as follows:

- BCF
- HCF
- BCF and HCF
- BCF, HCF and SCF
- No cutting fluid, Environmental Variation Error (EVE)

The measurement aims at representing the operating conditions of the machine tool during a manufacturing process. The cycle takes in total 540 s and consists of three parts: In the first part, the inclination of the levels is evaluated at 8 different points during 250 s while the cutting fluid is acting. In the second part of the cycle, the cutting fluid stops for 140 s and finally it is restarted again for another 150 s. This cycle is repeated 160 times, leading to a measuring time of 24 h, in which the cutting fluid is acting during the first 12 hours. In the last 80 repetitions the cutting fluid is completely turned off, in order to bring again the machine into equilibrium with the environment. The EVE test is carried out for 48 hours.

3 Measurement results

The external unit controlling the temperature of the fluid uses an on-off control strategy, which causes oscillations of the temperature of the fluid, as it can be seen in Figure 2. In this figure, the vertical lines delimit the time when the cutting fluid is acting, corresponding to the first 12 h of the measurement.

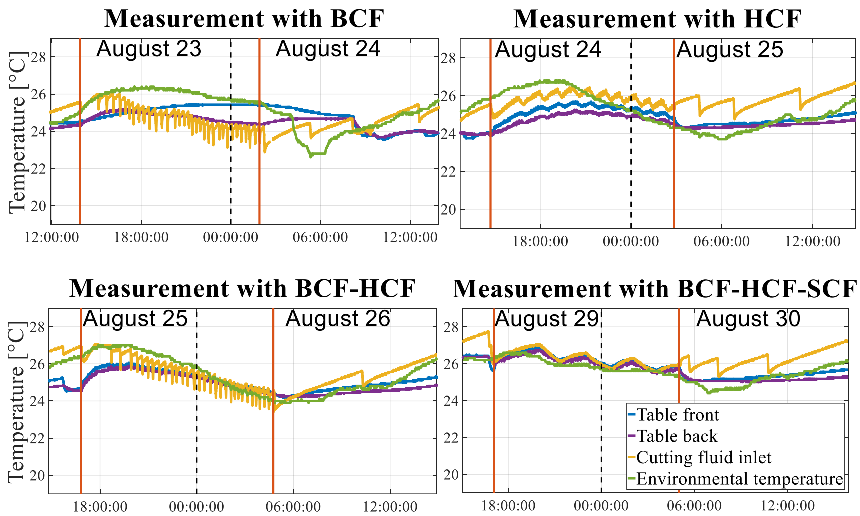

Figure 2 Measured temperatures with different cutting fluid supply modes. See Figure 1 for the location of the sensors

The effect of the oscillations of the cutting fluid temperatures can directly be observed in the thermal response of the machine. As displayed in Figure 2, the temperature of the table oscillates with the same frequency as the temperature of the cutting fluid when HCF or BCF-HCF-SCF is used. On the other hand, this periodicity is filtered out for the case of BCF and BSC-HCF, due to the higher frequency of the on-off control. Focusing on the gradient between the back and the front part of the table, the use of modes of delivering the cutting fluid which affect the cutting space more homogenously, namely BCF-HCF-SCF, leads to reduced gradients. As the BCF does not affect the whole table homogenously, a higher gradient between the back and the front part of the table is created, opposed to the other study cases. In general, the cutting fluid succeeds in bringing the table temperature closer to the environmental one. The temperature sensor measuring the air of the working space shows a sudden variation when applying the cutting fluid. When the HCF is activated, the temperature drop in the air of the working area is around 4 °C.

Analyzing the measured machine response with the electronic level, it can be observed that inclination difference of the Y-axis of the machine does not show a remarkable dependency on the cutting fluid. The fluidic media does not act directly on the Y-axis and therefore has not a big impact on the change of the deformation inclination in this part. On the other hand, the inclination of the Z-axis is considerably affected by the cutting fluid. In all measurement cases where the BCF is present, a variation of the inclination can be observed, shown in Figure 3. The significant deformations are located in structural parts of the machine where the fluid is directly acting on. This implies that the cutting fluid has a local effect, which will propagate to the rest of the machine structure with time. The introduction of the cutting fluid leads to a reduction of the temperature of the part of the Z-axis bed further away from the working space, which translates in a positive inclination. In the first hours, the front side is not greatly affected by this temperature reduction, causing a negative relative inclination from the middle to the front. Once the temperature of the Z-axis homogenizes, the inclination of the front part also becomes positive. For the measurement of the inclination with BCF, only the data of the first 12 h are available due to an error of the NC code.

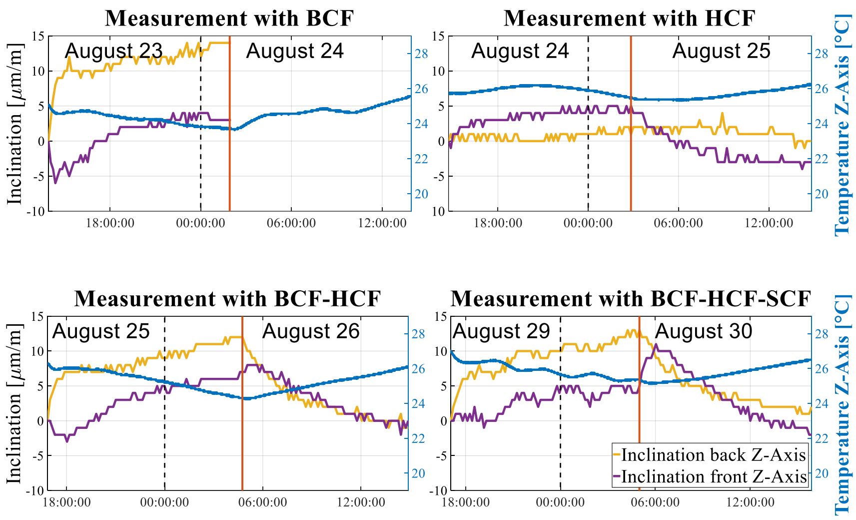

Figure 3 Measured Inclinations and Temperature of the Z-axis

The use of only HCF does not seem to have a great impact on the angular measurements regarding the Z-axis. The cutting fluid is not acting on the Z-axis bed for HCF, not leading to significant variations of the inclination greater than the one caused by the environmental influences. This explains the localized effect of the cutting fluid.

In order to assess the influence of the environment, an EVE test is conducted over 48 hours in summer season. The machine under investigation is located in a non-temperature controlled shop floor. The sensors measuring the environment capture a temperature variation over time of 3 °C / 12 h and a maximum vertical gradient of 0.8 °C / 2 m.

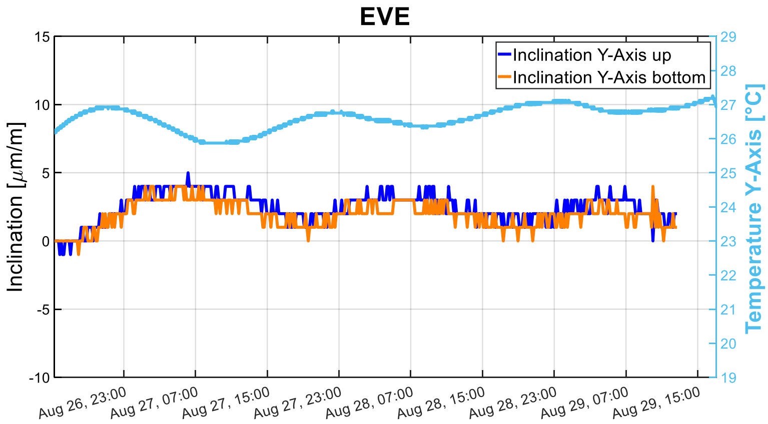

Figure 4 Measured Inclinations of the Y-axis for EVE test

Figure 4 displays the variation of the inclination of the Y-axis in the EVE test. The measured values show a similar periodicity of 24 h as the one shown by the temperature of the Y-axis structure. The thermal response of the Y-axis has a higher sensitivity to environmental temperature changes than the Z-axis. The higher surface area and lighter mass leads to a higher sensitivity of the Y-axis structure compared to the Z-axis, which is located on the machine bed.

4 Conclusions and Outlook

The present study shows how the different supply modes of the cutting fluid affect the accuracy of the machine tool. Firstly, the temperature response of the machine table is presented as a representative response of the temperature field of the whole structure. The table temperature follows the oscillations of the cutting fluid temperature, measured in the inlet stream after the control unit. When there is a fast temperature variation of the cutting fluid, the table filters out these variations, as shown for the cases of HCF and BCF-HCF. This shows that the temperature regulation of the cutting fluid plays a significant role for the temperature distribution within the working space.

Secondly, this work focuses on the structural response of the Y- and Z-axis. The variation of the inclination of the Y-axis is not affected by the cutting fluid. On the other side, the EVE test shows a variation of the inclination of the Y-axis similar to the environmental temperature. The cutting fluid has a clear effect on the deformation of the Z-axis, especially when the BCF is activated. The temperature gradient induced by the fluid leads to a positive inclination on the back part of the Z-axis, with a fast variation at the beginning. The front part of the Z-axis shows a delayed response, as the cutting fluid needs several hours to homogenize the temperature of the whole machine bed. This works illustrates that the cutting fluid directly affect the precision of the measured axes.

The conducted measurements provide a foundation for further enhancements of the machine design. The introduction of the BCF from more than one side of the Z-axis could homogenize the temperature distribution of the structure, potentially reducing the inclination variation between the front and the back part of the Z-axis in the first 12 h of the manufacturing process. This work shows the effect of the control strategy of the cutting fluid. Control units that regulate the cutting fluid temperature in smoother way could also have a positive effect reducing geometric errors of the machine. A systematic study of the influence of the selected reference temperature for the control is to be considered. An alternative to the current reference temperature could be the ground temperature, measured about 100 mm below the floor, which captures the damped environmental temperature variations.

In further research, the measured deviation of the linear axes can be used for compensation purposes. A model-based compensation approach reading the measured values from the electronic level can reduce the thermal errors induced by the cutting fluid. A model representing the kinematic chain of the machine is necessary. The measured deviations can be the input for the model, being the output the error at the tool center point (TCP).

5 Acknowledgments

The authors would like to thank the Swiss Federal Office for Professional Education and Technology (CTI) for their financial support.

6 References

[1] Mayr, J., Jedrzejewski, J., Uhlmann, E., Alkan Donmez, M., Knapp, W., Härtig, F., Wendt, K., Morikawi, T.,Shore, P., Schmitt, R., Brecher, C., Würz, T., Wegener, K., 2012, Thermal issues in machine tools, CIRP Annals - Manufacturing Technology, 61/2:771–791.

[2] Ibaraki, S., Blaser, P., Shimoike, M., Takayama, N., Nakaminami, M., et al., 2016, Measurement of thermal influence on a two-dimensional motion trajectory using a tracking interferometer, CIRP Annals - Manufacturing Technology, 65/1:483–486.

[3] ISO 230, 2007, Test code for machine tools -- Part 3: Determination of thermal effects, Geneva, Switzerland.

[4] Gebhardt, M., Knapp, W., Wegener, K., 2014, Messung thermischer Einflüsse auf Werkzeugmaschinen zur steuerungsseitigen Fehlerkorrektur am Beispiel von Dreh-/Schwenkachsen, Technisches Messen, 81/4:158–165.

[5] Weikert, S., 2004, R-Test, a New Device for Accuracy Measurements on Five Axis Machine Tools, CIRP Annals - Manufacturing Technology, 53/1:429–432.

[6] Mayr, J., Egeter, M., Weikert, S., Wegener, K., 2015, Thermal error compensation of rotary axes and main spindles using cooling power as input parameter, Journal of Manufacturing Systems, 37:542–549.

[7] Ibaraki, S., Hong, C. F., 2012, Thermal Test for Error Maps of Rotary Axes by R-Test, Key Engineering Materials, 523–524:809–814.

[8] Bitar-Nehme, E., Mayer, J. R. R., 2016, Thermal volumetric effects under axes cycling using an invar R-test device and reference length, International Journal of Machine Tools and Manufacture, 105:14–22.

[9] Mayr, J., Müller, M., Weikert, S., 2016, Automated thermal main spindle & B-axis error compensation of 5-axis machine tools, CIRP Annals - Manufacturing Technology, 65/1:479–482.

[10] Gomez-Acedo, E., Olarra, A., Zubieta, M., Kortaberria, G., Ariznabarreta, E., et al., 2015, Method for measuring thermal distortion in large machine tools by means of laser multilateration, The International Journal of Advanced Manufacturing Technology, 80/1:523–534.

[11] Brecher, C., Fey, M., Wennemer, M., 2016, Volumetric measurement of the transient thermo-elastic machine tool behavior, Production Engineering, 10/3:345–350.

[12] Mayr, J., Gebhardt, M., Massow, B. B., Weikert, S., Wegener, K., 2014, Cutting fluid influence on thermal behavior of 5-axis machine tools, Procedia CIRP, 14:395–400.

[13] Pavliček, F., Beer, Y., Weikert, S., Mayr, J., Wegener, K., 2016, Design of a Measurement Setup and First Experiments on the Influence of CO2-cooling on the Thermal Displacements on a Machine Tool, Procedia CIRP, 46:23–26.

[14] ISO 10791, 2015, Test conditions for machining centres -- Part 1: Geometric tests for machines with horizontal spindle (horizontal Z-axis).

[15] ISO 230, 2012, Test code for machine tools -- Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions, Geneva, Switzerland.