Special Interest Group meeting
Thermal Issues
March 2024
www.euspen.eu

A thermal error reduction of CNC grinding machine by FEA-based cooling system design and thermal compensation

Otakar Horejš[1], Martin Mareš[1], Peter Kohút[1], Matěj Sulitka[1]

[1]*Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Production Machines and Equipment, RCMT, Horská 3, 128 00 Prague, Czech Republic*

o.horejs@rcmt.cvut.cz

Abstract
There are many causes for workpiece inaccuracy. However, thermal errors of machine tools are usually the most significant cause that affects the accuracy of workpieces, despite the rapid development in machine tools lasting several decades. This paper presents an enhancement of a CNC grinding machine accuracy by reduction of thermal error using an external cooling system design based on FEA in combination with thermal error compensation. First, offline thermal error modelling using finite element analysis (FEA) was caried out to investigate transient thermal deformations of the CNC grinding machine. The external cooling of the wheel head is proposed based on FEA analysis to significantly reduce angular displacements of the wheel head. Second, a thermal error compensation based on transfer function (TF) was developed. The compensation model is built on the experimental measurements on the CNC grinding machine with and without application of the external wheel head cooling. An added benefit of the external wheel head cooling proposed by FEA is that it leads to simplified structure of the thermal error compensation model, and it also reduces the compensation model inputs. The CNC grinding machine accuracy improvements were around 80% in average in the X direction when compared with the uncompensated state.

Thermal error compensation, Grinding machine, Finite element method (FEM), Cooling system design

1. Introduction

Nowadays, more frequently the machine tool builders take responsibility for the control of thermally induced displacements. This change took place because machine tool users realised that comparable machine tools can show significantly different thermal errors and that in some machine tools most of the energy supplied to the machine tool is used to stabilise the temperatures [1]. Thermal errors at the tool centre point (TCP) are usually the most critical errors in machining. Furthermore, thermal errors at TCP are often the most difficult to reduce. Therefore, research in this area is of great interest and with a very active research community.

Different approaches exist to minimize thermal errors. In general, it is possible to divide the thermal error issue solution into three basic groups: design of the machine tool system to reduce sensitivity to heat flow (e.g. thermally symmetrical machine tool structure, thermal insulation etc.), temperature control of machine tool and its environments (e.g. control of machine tool cooling system etc.), and compensation of the thermal errors [2].

This study investigates grinding machine thermal errors reduction by external cooling system design based on finite element analysis (FEA) in combination with thermal error compensation based on transfer function modelling (TF).

2. Grinding machine

The tested machine was a prototype of a multifunction grinding machine. This CNC grinding machine is designed for grinding large heavy cylinders with a maximum diameter of up to 1 000 mm, a length of 12 m and a weight of 8000 kg when clamped between centers and 12 000 kg when clamped in steadies. Linear motors are applied in X and Z-axes for maximum grinding precision including grinding workpiece diameters (backlash-free movement in X and Z axes). The CNC grinding machine is equipped with control system Sinumerik 840D sl, Sinamics S120 converters and Simotics linear motors. The grinding unit in the basic version has two feed axes with grinding wheel for external grinding (S1 and S2) and one feed axis for internal grinding (S3), see Fig. 1. An internal cooling circuits are an integral part of the designed prototype of the CNC grinding machine for temperature control of the critical components such as linear motors in X and Z direction, rotary axis B1, etc.

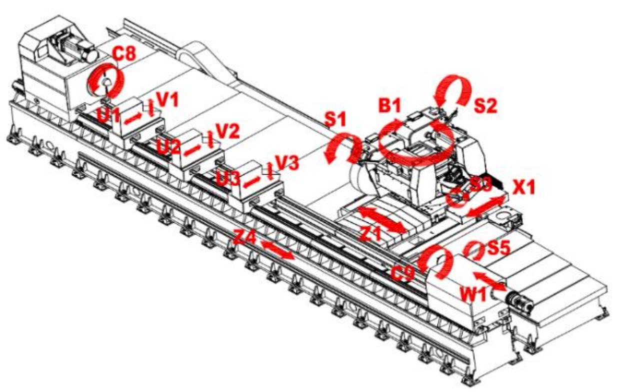

Figure 1. Multifunction grinding machine with feed axes description.

3. FEA-based cooling system design

To investigate transient thermal deformations of the CNC grinding machine, the FEM of the grinding machine was developed, see Fig. 2.

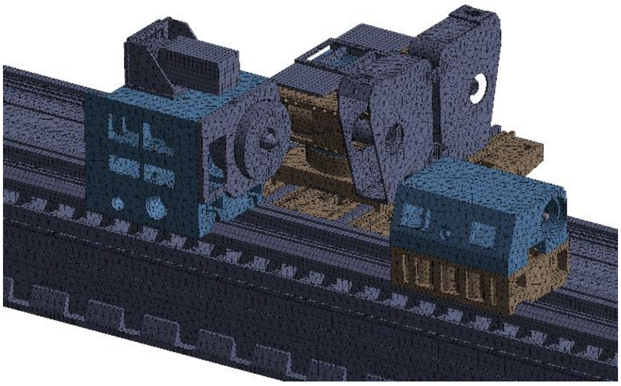

Figure 2. FEM model of the grinding machine.

The boundary conditions of the FEM (Fig. 2) were adjusted based on the experimental results during the continuous external cylindrical grinding including process liquid impact. The experiment was carried out with the constant wheel rotational speed 660 rpm in feed axis S2 (wheel peripheral speed was 30 m.s^{-1}) until the steady state followed by a cooling phase). The target machine was placed in a manufacturer's shop floor. The shop floor is a non-air-conditioned huge open space equipped with a row of production machines.

Temperature field of the wheel head obtained by FEA (after 11 hours and 29 minutes) is shown in Fig. 3 (left). As the wheel head has a thermally unsymmetrical structure, it results in significant angular rotation of the spindle axis (angular displacement of the wheel head) which is shown in Fig. 4.

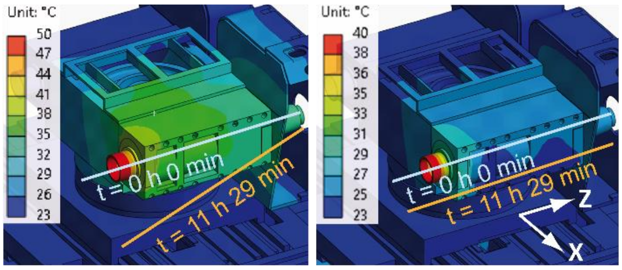

Figure 3. Thermally induced displacements of the wheel head without/with the external cooling (left/right) obtained by FEA (angular displacements of the spindle axis is illustrative).

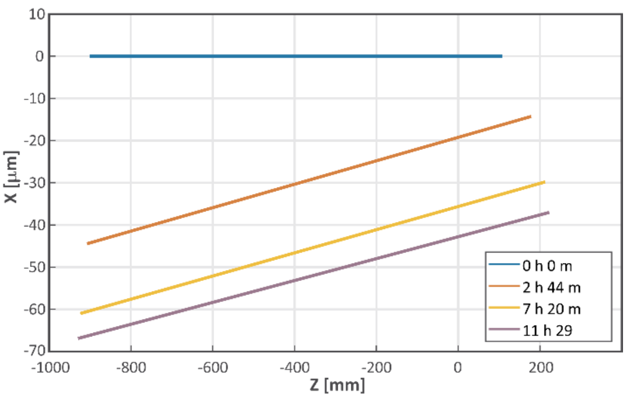

Figure 4. FEA results - angular displacements of the wheel head in time without the external cooling.

To reduce angular displacements of the wheel head, the external cooling of the wheel head front side was proposed, see Fig. 5. The external cooling employ process liquid to cool down surfaces close to the front and rear bearing of the spindle S2. This approach represents convenient solution because of its cost-effectiveness and ease of implementation (non-invasive).

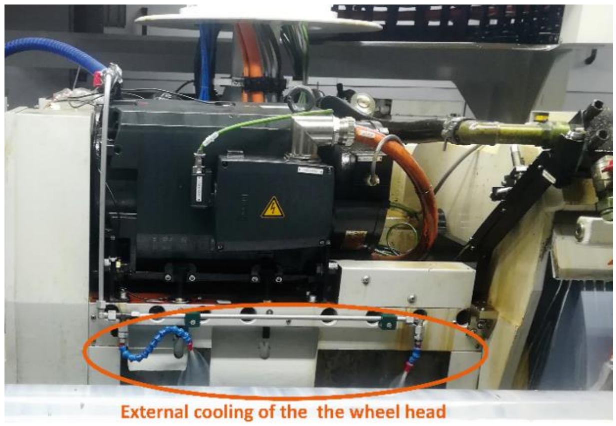

Figure 5. External cooling of the font side of the wheel head.

To verify the effectiveness of a non-invasive measure to homogenize the temperature field of the wheel head (to reduce angular displacements of the wheel head) before its implementation, the FEA with appropriate boundary conditions was performed.

Temperature field of the wheel head with application of the external cooling obtained by FEA (after 11 hours and 29 minutes) is shown in Fig. 3 (right).

Angular displacements of the wheel head in time with application of the external cooling are shown in Fig. 6

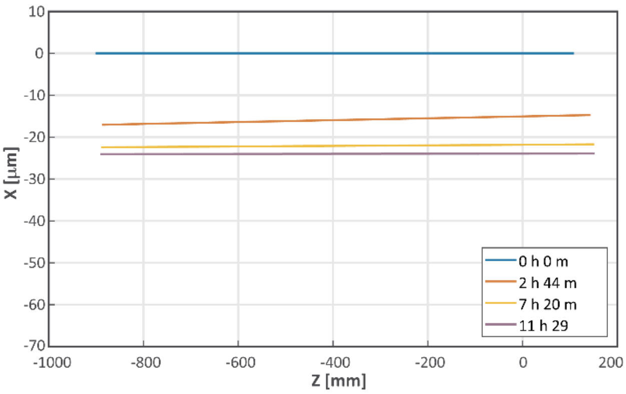

Figure 6. FEA results - angular displacements of the wheel head in time with the external cooling.

The positive effect of the external cooling to reduce thermally induced angular displacements of the wheel head is evident by comparison of results obtained by FEA (see Fig. 4 and Fig. 5).

The external cooling remarkably helps to linearize the thermal behaviour of the wheel head.

The CNC grinding machine was subsequently equipped with the external cooling based on the results of the FEA as shown in Fig. 5.

3. Thermal error compensation model

The inevitable remaining thermal deformations of the wheel head (after application of external cooling) can be further reduced by means of indirect (software) compensation. Therefore, the thermal error compensation model was investigated, parallelly to the FEA. Specifically, the thermal error compensation based on the TF modelling (see [3]) was developed. Limits of these TF models (linear parametric single input single output models) and its capability of industrial applicability are discussed in [4]. The developed model is focused on compensation of thermally induced displacements at the TCP in the X direction. The thermal errors in the X direction directly affect diameter of the workpiece which is critical dimension in case of the cylindrical grinding.

The development of the thermal error compensation model involves conducting experiments to assess machining accuracy influenced by thermal effects. The experiments were carried out on the prototype of the grinding machine without application of the external cooling presented in section 2.

Nine experiments were carried out within the wheel head activity (n_{S2}), the movement in the linear axes X and Z (feed rates v_X, v_Z), rotation of the workpiece n_{C8} and flowrate of the process fluid ($Q_{cool\text{-}WP}$). The CNC grinding machine was equipped with the grinding wheel which has a diameter of 900 mm. Each experiment consisted of a part of transient behaviour between two thermodynamic equilibria (the grinding machine in approximate balance with its surroundings and the grinding machine steady state during heat source activity) ended after one work shift (6 to 8 hours). The experimental setup is summarised in Fig. 7.

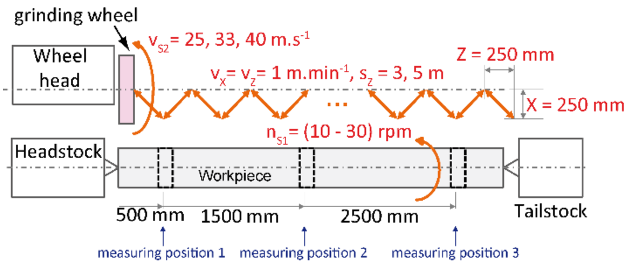

Figure 7. Schema of experimental setup with wheel head activity during grinding wheel rotation.

The scheme of the thermal error compensation model is shown in Fig. 8.

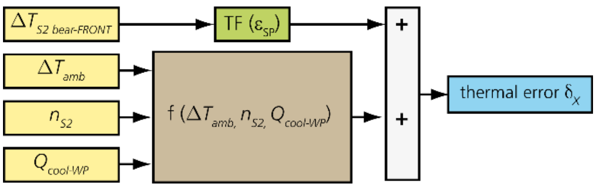

Figure 8. The scheme of the thermal error compensation model based on TF.

The key model inputs are the temperature measured close to the front bearing of the wheel head at feed axis S2 ($T_{S2\ bear\text{-}FRONT}$), the ambient temperature (T_{amb}), rotational speed of the spindle S2 (n_{S2}) and the flowrate of the process fluid ($Q_{cool\text{-}WP}$). The influences of the movements of the linear axes X and Z and the rotation of the workpiece (n_{C8}) are negligible.

The compensation model consists of 1 TF with 1 input (the front bearing of the wheel head at feed axis S2 $T_{S2\ bear\text{-}FRONT}$). The other involved parameters (T_{amb}, n_{S2} and $Q_{cool\text{-}WP}$) are employed as inputs to the correction function *f* (T_{amb}, n_{S2} *and* $Q_{cool\text{-}WP}$), (see Fig. 8) to incorporate other influences which affects resultant thermal errors in thew X direction.

4. Verification tests using the test workpieces

The enhancement of CNC grinding machine accuracy through minimisation of thermal errors by the external wheel head cooling design proposed with help of FEA and the thermal error compensation based on TF (section 3) were verified by grinding the test workpieces, see Fig. 9. Each verification test consists of cylindrical grinding of the 14 test workpieces shown in Fig. 9 machined in approximately 30 minutes interval. Some of the verification tests included process break (cooling phase without any feed axis movements) to simulate real condition. Thus, each test lasts approximately 5 to 7 hours.

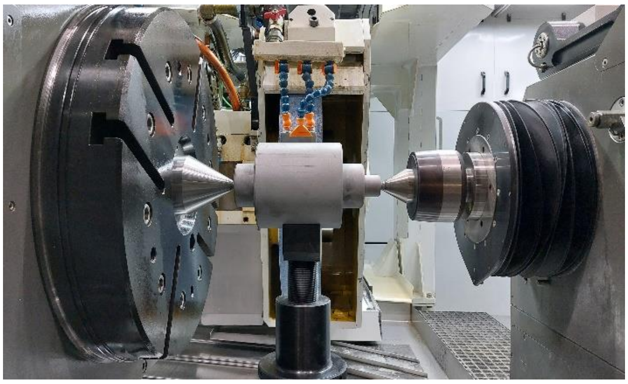

Figure 9. Test workpiece for the verification tests clamped between centers on the CNC grinding machine.

The same grinding wheel with a diameter of 900 mm was employed as in section 3. A rotational speed of the spindle S2 was 570 min^{-1}.

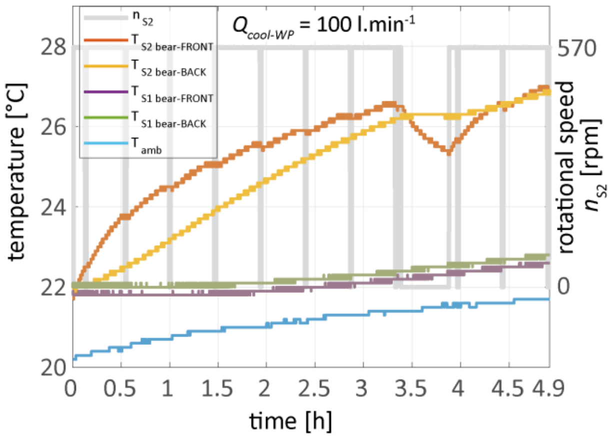

Figure 10. Measured temperatures and model inputs during the verification test with the test workpiece.

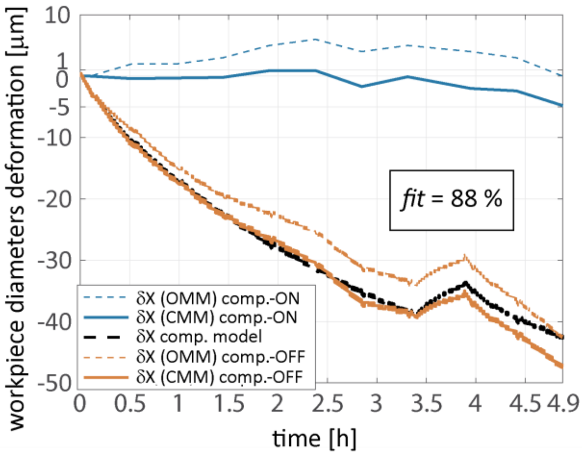

Figure 11. Measured (thermally compensated) diameters of the test workpieces using OMM and CMM, compensation model prediction of thermal errors in the X direction and off-line calculated (reconstructed) state of the test workpiece diameters without thermal error compensation during the verification test.

The flowrate of the process fluid ($Q_{cool\text{-}WP}$) was changed from 50 l.min^{-1} to 100 l.min^{-1}. The verification tests were performed with active/non-active compensation model of thermal errors (see section 3).

The machined diameters of the test workpieces were measured using 2 methods. First, on-machine measurement (OMM) using in-build measuring device with a pair of contact displacement sensors. Second, measurements of test workpieces diameter at several positions along the test workpieces using coordinate measuring machine (CMM) from Zeiss (ACCURA), see [5].

Experimental tests with test workpiece demonstrate a significant reduction of thermal errors in the X direction by means of the thermal error compensation based on TF.

Example of verification test results including process break is shown in Fig. 10 and Fig. 11.

The measured temperatures and model inputs during the verification test with the test workpiece are depicted in Fig. 10 (constant flowrate of process liquid $Q_{cool\text{-}WP}$ = 100 l.min^{-1} during the cylindrical grinding).Fig. 11 represents measured (thermally compensated) diameters of the test workpieces using OMM and CMM measuring method, compensation model prediction of thermal errors in the X direction and off-line calculated (reconstructed) state of the test workpiece diameters without thermal error compensation during the verification test.

The approximation quality of the simulated behaviour is expressed by global approach based on the least square method (*fit*; a percentage value where 100% would equal a perfect match of measured and simulated behaviours) described in [6]

$$fit = \left(1 - \frac{\|\delta X_{mea} - \delta X_{sim}\|}{\|\delta X_{mea} - \overline{\delta X}_{sim}\|}\right) \cdot 100. \quad (1)$$

where δX_{mea} value is the measured output (thermal deformation in X direction), δX_{sim} is the simulated/predicted model output, and $\overline{\delta X}_{sim}$ expresses the arithmetic mean over time of the measured output. The overall *fit* value is 88 % for this specific verification test with the test workpiece.

Furthermore, the number of the model inputs can be significantly reduced by introducing the external cooling system proposed by FEA (implementation of the external cooling of the wheel head front side is depicted in Fig. 5). It is due to the homogenization of the wheel head temperature field caused by the external cooling system designed using FEA. Thus, the external cooling system affects positively the linearization of thermal errors of the grinding machine in the X direction. In this case, the structure of the thermal error compensation model introduced in Fig. 8 can be significantly simplified. The correction function $f\ (T_{amb},\ n_{S2}\ and\ Q_{cool\text{-}WP})$, presented in Fig. 8, can be completely omitted.

5. Conclusion

The main objective of the presented study was the enhancement of CNC grinding machine accuracy through minimisation of thermal errors by the external wheel head cooling design proposed with help of FEA and the thermal error compensation based on TF.

The original design of the grinding machine and position of the heat sources causes a significant angular rotation of the spindle axis (feed axis S2). First, the proposed external wheel head cooling leads to homogenization of the wheel head temperature field. Consequently, it contributes to the linearization of thermal errors of the grinding machine in the X direction. An added benefit of the external wheel head cooling proposed by FEA is that it enables simplification of the thermal error compensation model, and it also reduces the required compensation model inputs.

The application of the wheel head cooling in combination with the thermal error compensation significantly improve the grinding machine accuracy, resulting in the residual errors (X direction) of less than 5 μm (see Fig. 11).

References

[1] Mayr J., et al. 2012 Thermal issues in machine tools. CIRP Annals – Manufacturing Technology 61(2) 771−791

[2] Weck M. et al. 1995 Reduction and Compensation of Thermal Errors in Machine Tools. Annals of the CIRP **44** (2) 589-598

[3] Mareš M. et al. 2020 Thermal error compensation of a 5-axis machine tool using indigenous temperature sensors and CNC integrated Python code validated with a machined test piece. *Precision Engineering* **66**(1) 21-30.

[4] Horejš O and Mareš M. 2022 Limits of linear parametric models for thermal error compensation of a large grinding machine. *Special Interest Group Meeting on Thermal Issues* ETH, Zurich, Switzerland.

[5] Zeiss, Coordinate measuring machines Bridge CMMs, https://www.zeiss.com/metrology/products/systems/cmm/bridge-type-cmms.html.

[6] Ljung L., 2015, System Identification Toolbox™ User's Guide, The MathWorks