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Thermal issues in 5-axis machine tools

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Abstract

This paper describes research carried out with the Mori Seiki NMV 5000 DCG machine tool at IWF / ETH in Zurich in the field of precision of rotary axes influenced by thermal effects. Presented are an extended physical compensation model, the thermal behavior of the NVM 5000 DCG under the influence of cutting lubricant, and the evaluation of the thermal behavior using an especially designed test piece. A physical model, which computes the thermal location errors and the table diameter error E_{R0T} of the machine tools rotary axes, is extended by a cooling model. The cooling model computes the inlet temperature of the internal cooling system based on the power input to the drives. The thermal test piece allows evaluating a combination of thermal errors of the rotary and swiveling axis and the main spindle. For evaluation of the thermal test piece a Coordinate Measuring Machine (CMM) can be used and no additional machine tool measuring equipment is necessary. The comparison of measurements with and without cutting lubricant shows that the inlet temperature of the cutting lubricant has a significant influence on the overall thermal behavior of the machine tool.

Keywords: Thermal behavior, five-axis machining, thermal test piece, cutting lubricant

1 INTRODUCTION

The accuracy of machine tools is the keystone to modern precision manufacturing. Often therefore three axis machine tools are the choice for manufacturing of high precision parts in milling. Nevertheless, there is a growing demand on high precision five-axis machined workpieces. Thermal influences of machine tools are a large error source on machined parts [1].

In three different parts the understanding and description of thermal behavior of five-axis machine tools is pushed forward. Chapter 2 introduces into an existing model of a rotary and swiveling unit the influence of internal cooling. Chapter 3 describes the evaluation of thermal errors on machine tools with rotary axes using a thermal test piece, which is especially designed. In chapter 4 the influence of cutting lubricant to the overall thermal behavior of machine tools is presented. A conclusion is given in chapter 5 and an outlook of further research work in chapter 6.

2 MODELLING INTERNAL COOLING OF A ROTARY SWIVELLING AXIS UNIT

In [2,3] a physical prediction model for the compensation of thermally induced errors of rotary axes is presented. The cooling power $\dot{Q}$ used in this model is provided by online measurements: the volume flow $\dot{V}$, the inlet temperature T_{in} and the outlet temperature T_{out} of the cooling unit as well as the heat capacity c_p and density ρ of the cooling fluid are measured and used for computing the cooling power according to:

$$\dot{Q} = \dot{V} \cdot c_p \cdot \rho \cdot (T_{out} - T_{in}) \quad (1)$$

The coolant outlet temperature (= flow into machine tool) of the cooling unit under investigation is controlled according to the bed temperature of the machine tool. After entering the machine tool, the cooling fluid flow is split in two cooling streams:

- one stream for cooling the B-axis ($\dot{V}_B$) and
- one stream for cooling the C-axis ($\dot{V}_C$).

Measured temperatures are the inlet temperature T_{in} and the two outlet temperatures T_B and T_C of the B-axis and C-axis respectively, as well as the environmental temperature T_E. For modelling the cooling power, the inlet flow $\dot{V}_{in}$ and the electric power consumption of the cooling compressor have to be measured. The inlet flow $\dot{V}_{in}$ is measured with a flow meter. To evaluate the electric power consumption of the cooling compressor the voltage is directly measured and the current is measured using the Hall effect.

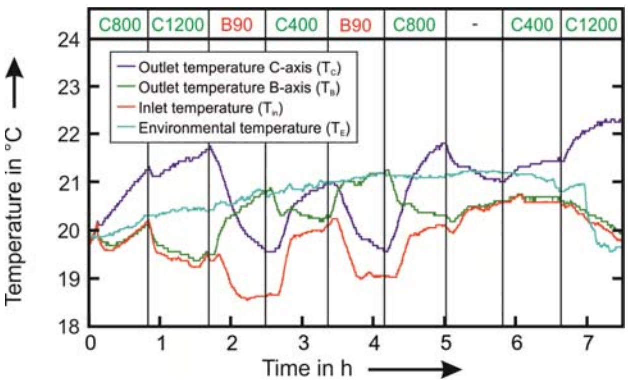

Figure 1: Measured temperatures according to [4]. Green labels: C-axis rotational speed, red labels: B-axis angular position.

In Figure the coolant outlet temperature of the machine tools' C- (blue curve) and B-axis (green curve), the coolant inlet temperature (red curve), and the environmental temperature (cyan curve) during an arbitrarily chosen load cycle are shown. The load cycle is illustrated on top of Figure by the green and red labels. It can be seen that the inlet temperature T_{in} is influenced significantly by the axis motion.

The cooling power of a chiller $\dot{Q}$ depends on the coefficient of performance (COP) and the power consumption $\dot{W}$ of the chiller. Therefore an exponential function modelling the power consumption $\dot{W}$ is developed.

$$\dot{W} = k + \left(\frac{P_C}{l}\right)^a + \left(\frac{P_B}{m}\right)^b \quad (2)$$

The power consumption model of the cooling unit given in equation (3) consist of five constant parameters a, b, k, l and m and the power consumption of B- and C-axis P_C and P_B

which are read out of the control unit of the NMV 5000 DCG. The constant parameters of equation (3) are found by a fitting procedure using measured power consumption of the chiller. For identifying the constant parameters of equation (3), different long-time measurements have been used. The procedure used is a routine of Matlab®. The power consumption of the machine tool's rotary axes show peaks when changing the initial state due to acceleration and deceleration sequences. To avoid incorrect fitting the measured power consumption curve of the chiller, therefore was filtered with a low pass filter. In Figure 2 computed and measured cooling power of the chiller are shown.

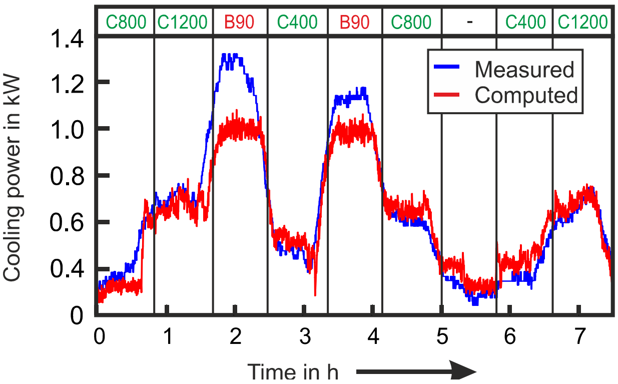

Figure 2: Computed and measured cooling power of the chiller according to [4].

The coolant inlet temperature T_{in} is computed with the cooling power of the chiller and information of the mass flow and heat capacity of the coolant. As equations (2) and (3) explain that the coolant inlet temperature T_{in} only depends on the axes power consumptions P_B and P_C.

With the introduced phenomenological cooling model the physical compensation prediction model introduced in [3] is extended. The extended model was used to carry out a compensated test-cycle. The results of the compensated test-cycle are compared to the results with the compensation model presented in [3] and to an uncompensated cycle. Figure shows these three different cases with the example of the Y-deviation of the C-axis (E_{Y0C}).

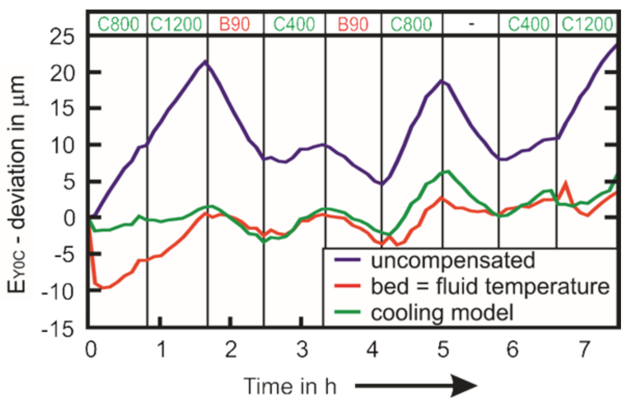

Figure 3: Thermally induced TCP error E_{Y0C} for uncompensated and compensated machine too according to [4].

Table 1: Error reduction with compensation models table (Notation according to [5])

	E_{Y0C}	E_{Z0T}	E_{R0T}	E_{A0C}
Compensation without cooling model in %	79	56	36	45
Compensation with cooling model in %	84	83	79	49

In Table 1, the improvement is shown by the mean deviations in %. Listed are the dominating thermally location errors induced by the rotary and swiveling axis unit of the machine tool under investigation.

3 THERMAL TEST-PIECE

Measurement systems and procedures for the characterization of the thermal behavior of machine tools typically are quite complex and cost intensive. Often users of machine tools do not possess such equipment. For several applications such as the qualitative comparison of different machine tools or the qualitative validation of a certain compensation algorithm, no high-resolution measurements are necessary. Analogue to geometric test pieces, a thermal test-piece is an alternative solution for such cases.

Figure shows the developed thermal test-piece. It is mounted on the machine tool table by 4 screws. For an explicit orientation of the test-piece, a mark for orientation is engraved after mounting. Different facings are milled with a defined time gap between each facing to identify thermally induced TCP-deviations in X-, Y- and Z-direction. Between milling of the faces, thermal load is induced by running the machine tool which cause thermal deviations. In the presented work, the thermal load is induced by a C-axis table rotation with 1200 rpm for one hour. After that the next facing is milled. The total load cycle consists of a warm-up phase of three hours (3 facings) and a cool-down cycle with no thermally induced load in the gaps of again three hours between the milling of the facings (3 facings).

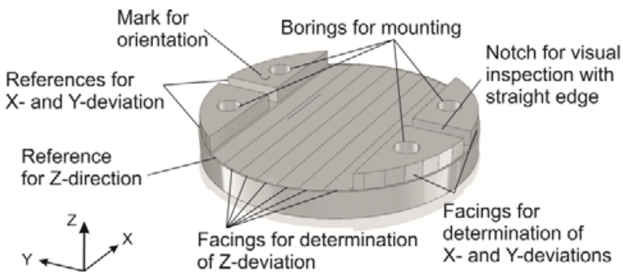

Figure 4: Thermal test-piece for qualitative evaluation of thermal deviations of the tool center point (TCP) in X-, Y- and Z-direction [6]

The rough geometry of the thermal test piece is premilled. During the thermal error test it is just finished with a depth of cut of only 0.1 mm with a finishing tool. The test-piece is mounted on the C-axis rotary table of the NMV 5000 DCG. For milling the facings for measuring the TCP-deviations in X- and Y-direction, the test-piece is orientated by the machine tool's C-axis. For each direction, the milling process is carried out at the same axes positions in the working envelope. Just the orientation of the C-axis position is changed. During the entire test-cycle, no axis movement in Z-direction is necessary. Thereby the geometric errors of the Z-axis can be neglected. For the determination of TCP-displacements in X- and Y-direction, the distance of the milled facings to their opposing reference facing are evaluated. Thereby the geometric errors of the X- and Y-axis can also be neglected. In each direction, a reference facing is milled before thermal load is induced. For evaluating thermal errors in X- and Y-direction, the distance to reference facings is measured, see Figure 5. This can be done by a CMM or manually, e.g. by a micrometer screw [5].

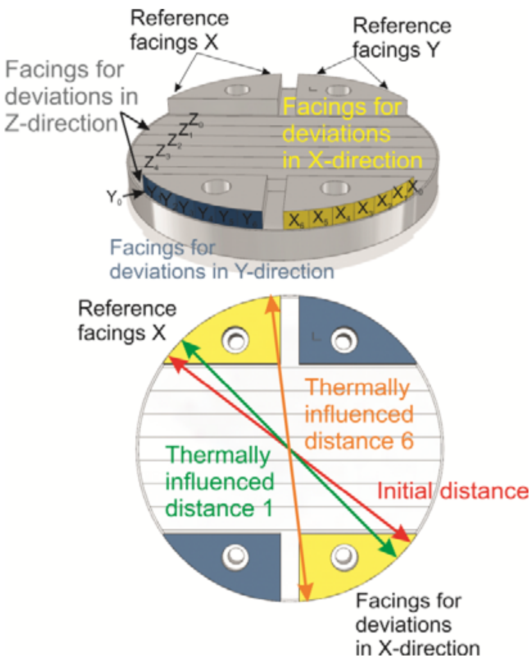

Figure 5: Evaluation of thermal test piece.

In

Figure 6 a milled thermal test piece is shown. The finished thermal test piece is under evaluation of thermally induced Z-deviations with a straight edge. Z-offset between the initial facing and the facing 1 milled after one hour test cycle, shown in the zoomed photograph, can be observed by the naked eye.

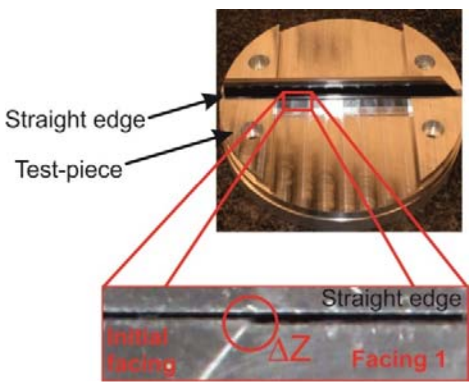

Figure 6: Manual evaluation of E_{Z0T} with a straight edge [6].

For a more detailed evaluation the thermal TCP-deviations on the thermal test piece are measured using a CMM. The results are compared to machine tool thermal error measurements, carried out using R-test. In Figure 7 the comparison of both measurements, with the example of the location error of C in Y-axis direction E_{Y0C} is shown. The measurements show that the proposed test piece accurately and reproducibly visualizes thermally induced TCP-deviations of five-axis machine tools.

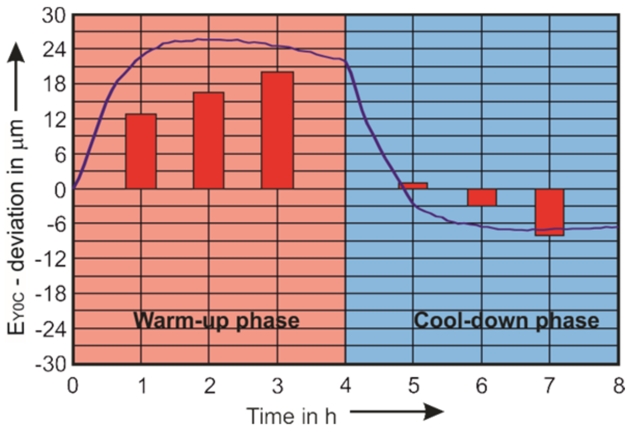

Figure **7**: Deviations of the C-axis in Y-direction during a warm-up cycle with a rotational speed of 1200 min^{-1} and a cool down phase with no rotational movement of the C-axis according to [6]. Blue line: deviations measured with R-Test. Red bars: deviations measured on the test-piece.

4 THERMAL INFLUENCE OF CUTTING LUBRICANT

The MoriSeiki NMV 5000 DCG has two separated internal cooling cycles, for the axis ball screws and main spindle and fot he rotary / swiveling axis, which are switched on when performing the measurements. While the outlet temperatures of the internal cooling systems are controlled by the bed temperature the cutting lubricant system has no re-cooler. The cutting lubricant is supplied to the process zone by flexible nozzles arranged on the machine tool spindle head. In addition the machine tool is equipped with a cutting lubricant shower what is used to flush out chips of the machine tool's rotary table and working envelope. The cutting lubricant shower is not considered in this research, because it is used only once after finishing a workpiece.

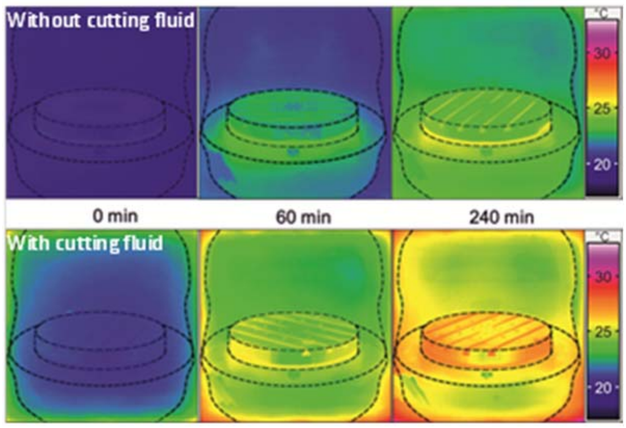

Figure 8. Thermography measurements of the rotary and swiveling axis with C-axis speed 600 rpm; the temperature

scale on the far right is given for uncorrected emissivity coefficients [7]

The influence to the cutting lubricant to the overall thermal behavior of machine tools is today not investigated in detail and still part of the research work. For a first evaluation of the temperature depended influences IR- measurements are performed. The C-axis of the machine tool is running with 600 rpm axis speed for at least four hours, once with and once without cutting lubricant. During the measurement cycles infrared (IR) image are taken at least every five minutes.

Examples of the IR measurement results for measurement time t = 0 min, t = 60 min, and t = 240 min are shown in Figure 8. The measurements show three important differences affected by the cutting lubricant:

1. Figure 8, diagrams on top shows, that without cutting lubricant the temperature of the C-axis and the B-axis corpus is influenced by internal heat produced, when running the machine tools C-axis. In the vicinity of the interface between the C-axis and the B-axis corpus both elements are heated. The IR images with cutting lubricant show a larger influence on the environment around the interface.
2. The temperature of the C-axis becomes higher, when cutting lubricant is spread over the structure.
3. The temperature of the B-axis corpus also increases due to the cutting lubricant.

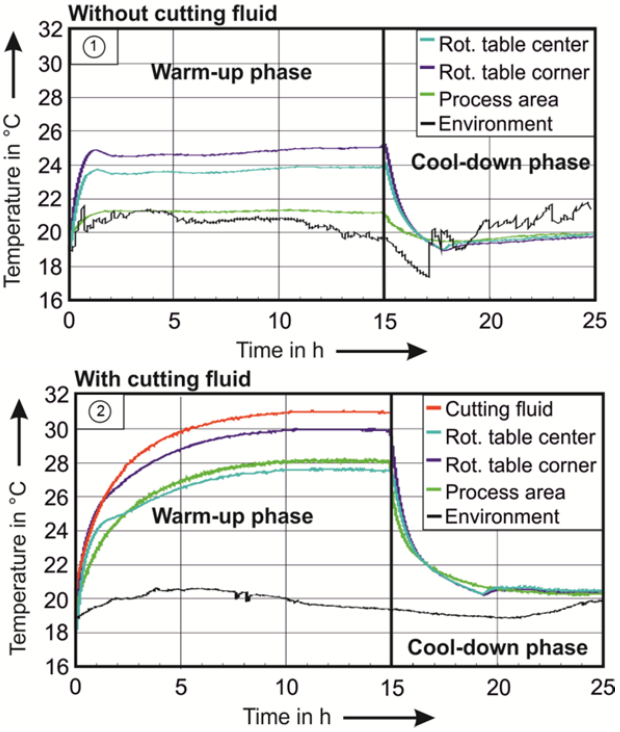

Figure 9: Temperature measurements during a C-axis operation of 15 h warm-up and 10 hours cool-down phase: 1) 600 rpm, without cutting lubricant 2) 600 rpm, with cutting lubricant

A two-step measurement procedure is chosen to quantify the influences of the cutting lubricant to the overall thermal behavior of the rotary and swiveling axis unit.

1. Measuring relevant temperatures of the machine tool's elements in the working envelope with and without cutting lubricant using contacting probes.
2. Measuring the thermally induced errors using the R-test set-up [8], once with and once without cutting lubricant supply.

Temperature measurements

In Figure 9 representative temperature measurement results are shown. In the diagrams temperature measurements of the warm-up phase (0 to 15 hours) and the cool down phase (15 to 25 hours) are shown. During warm-up phase the machine tool's C-axis is running with constant speed of 600 rpm. During the cool down phase all machine tool axes are in NC hold and the B position is zero.

When the C-axis is running with 600 rpm, a typical warm-up phase for the machine tool under investigation is recognized. The machine reaches steady state after about two hours. After that changes in temperatures are influenced by the environment and the internal cooling system. Nevertheless these effects are small, compared to the overall temperature rises measured on the machine tool's swiveling and rotary axis structure, shown in Figure 9-1.

In Figure 9-2 the measured temperature curves show that all temperatures in the working envelope are influenced by the cutting lubricant. By hydraulic friction the cutting lubricant is warmed-up reaching temperatures up to 31°C. Afterwards the temperature of the cutting lubricant is nearly constant. Nevertheless it takes almost ten hours till steady state is reached. After stopping the C-axis, the measured temperatures show no overshot as it is measured without cutting lubricant, shown in Figure 9-1. The cutting lubricant supply is stopped after the warm-up phase. It is recognized that, besides the warm-up phase, the cool-down phase is elongated compared to the measurements without cutting lubricant.

Measurement of thermally induced errors

In Figure 10 the measured thermally induced TCP-errors are shown. The thermal load is again C-axis rotation speed 600 rpm. Equal to the temperature measurements the warm-up phase is 0 to 15 hours measuring time and the cool-down phase is 15 to 25 hours measuring time. Due to a thermo-symmetrical design of the NMV 5000 DCG the location errors E_{X0C}, E_{B0C}, and E_{C0C} are small. The other measured thermally induced TCP-errors are significant and show large differences between the measurements with and without cutting lubricant. Dependent on the higher temperatures, measurements with cutting lubricant show larger TCP-displacements. Nevertheless the machine tool thermal errors reach steady state already within the first five hours of C-axis running. Additional differences in the thermal TCP-displacements can be observed. With cutting lubricant the table Z-position, E_{Z0T}, is rising to a maximum after about four hours. Afterwards this error slightly decreases. During cool down the errors E_{Z0T} and E_{Y0C} show an overshot after about 2 hours of cooling-down. These effects are not observed when measuring without cutting lubricant. A further difference can be observed regarding the displacement E_{A0C}. Without cutting lubricant the angular

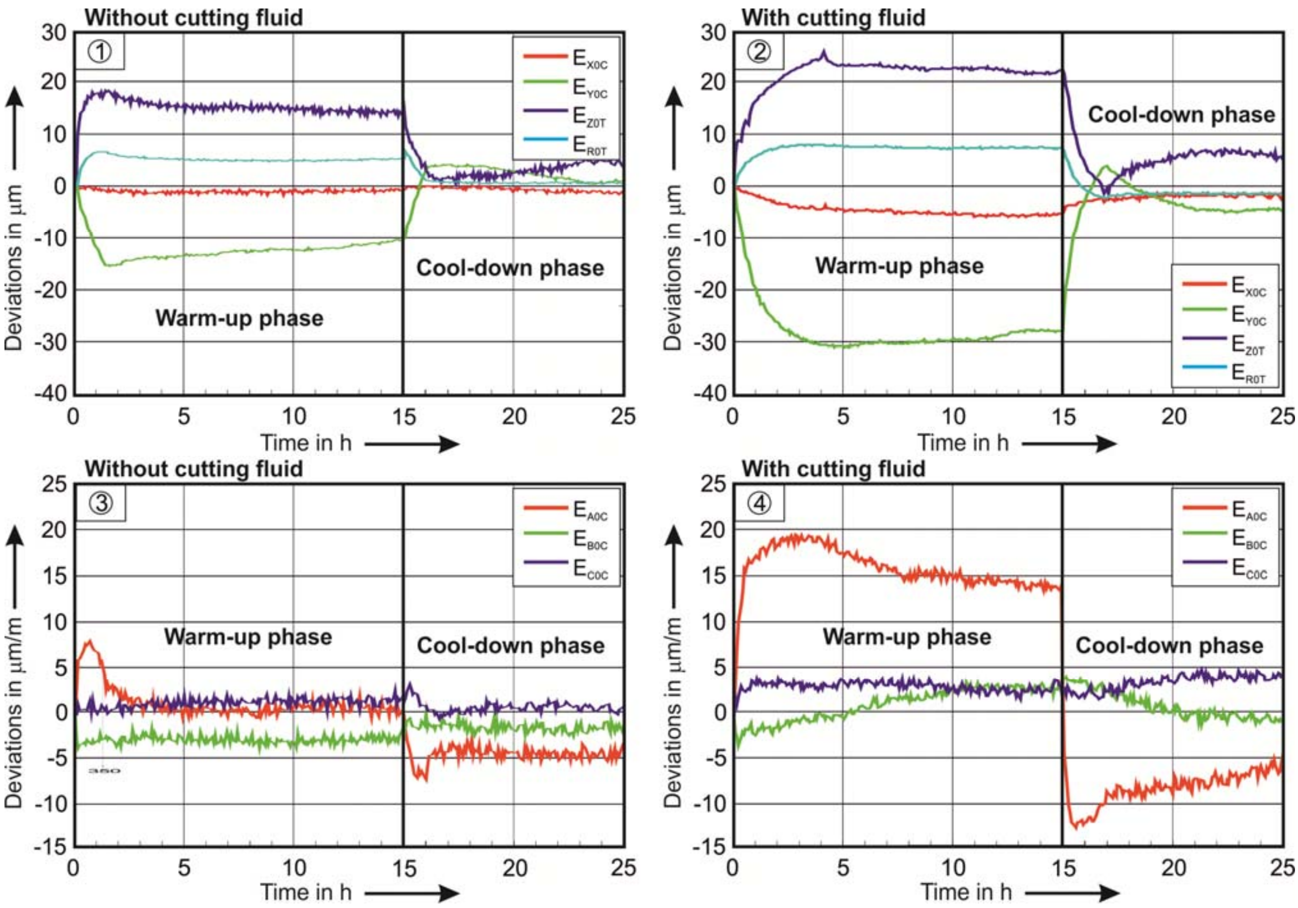

Figure 10: Errors measured with R-test during a C-axis operation of 15 h warm-up and 10 h cool-down phase: 1) Translational deviations, 600 rpm, without cutting lubricant 2) Translational deviations, 600 rpm, with cutting lubricant, 3) Rotational deviations, 600 rpm, without cutting lubricant, 4) Rotational deviations, 600 rpm, with cutting lubricant

thermal error E_{A0C} rises reaching a maximum after about two hours and it decreases to almost zero afterwards. In the opposite direction the same effect can be seen during cooling down. With cutting lubricant the displacement error E_{A0C} rise more and it is not decreasing until the machine tool table is stopped. During the cooling-down phase the error E_{A0C} shows an equal behavior with cutting lubricant to the behavior without cutting lubricant. The measurements show a significant change within the first 30 minutes of the cool-down phase. Nevertheless differences in the magnitude with and without cutting lubricant can be observed. After the overshoot in the first two hours of cooling-down the location error E_{A0C} became not zero. There is a remaining location error observed which slowly decreases. Finishing the measurements after 25 hours, the initial state of E_{A0C} is still not yet reached again.

Results of the experiment

The thermal behavior of NMV 5000 DCG is significantly different with and without cutting lubricant supply. The cutting lubricant temperature rises up to 31°C. The NMV 5000 DCG at ETH Zurich is not equipped with a re-cooling system. The cutting lubricant used is oil. If the temperature of coolants is lower than the environmental temperature, condensation on machine tool parts take place. This effect of condensation can often be seen on cooled machine parts. Therefore often the coolant temperatures are chosen to be higher than the environmental temperature. It is observed that due to the higher temperatures also the thermally induced errors increase. This effect influences the precision of machined workpieces during warm-up phase.

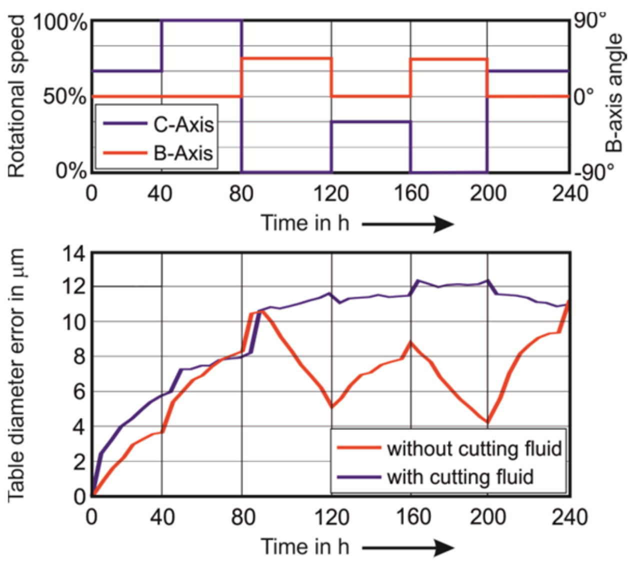

Figure 11: Table diameter error E_{R0T} of the C-axis table (bottom) during a combined load cycle of a B- and a C-axis movement (top).

The measurements of temperature and the thermally induced errors show that the time to reach steady state is elongated. Differences to the other thermal location errors are observed by E_{A0C}. The axis configuration of the NMV 5000 DCG does not allow compensating this error by any auxiliary axis movements. Other important effects are investigated during the cool-down phase, when stopping cutting lubricant supply and thermal load on the machine tool under investigation. Although with the use of cutting lubricant the thermally induced TCP-displacements are larger some positive aspects are observed. The machine was heated up with a varying load cycle with different C- and B-axis speeds, shown in Figure 11 top. Figure 11 bottom the measured table diameter error E_{R0T} is shown. Changing the axis speeds, what is a change in the power consumption of the axis drives, the table diameter error also changes significantly without cutting lubricant. Under the use of cutting lubricant these changes are “damped”. Therefore an axis speed change, e.g. cutting of different diameters or changing form turning mode to milling mode, is less critical under wet cutting with the MoriSeiki NMV 5000 DCG.

5 CONCLUSION

In this paper an extended physical compensation model for the rotary and swiveling axis unit of the NMV 5000 DCG is explained. Modelling the power consumption of the cooling unit takes into consideration change of the inlet temperature based on the actual axis power consumption of the machine tool B- And C-axis. With the extended compensation model all relevant thermal errors of the machine tool can be further reduced. It is shown that the relevant thermal errors can be reduced by 49% up to 84%.

Characterization of thermal errors of machine tools often requires expensive measurement equipment and time consuming measurements. Therefore a thermal test piece is developed to evaluate the thermal errors arising when the machine tool is running. The test piece can be evaluated with a CMM. As recognized, the thermal errors are in a range that it can be evaluated by the naked eye or with a micrometer screw. Therefore no expensive measurement equipment is necessary.

For an appropriate characterization of the thermal influences of NMV 5000 DCG machine tools it is shown, that the influence of cutting lubricant cannot be neglected. The thermal behavior changes significantly when using cutting lubricant. On the one hand the time to reach steady state is elongated for warm-up and cool-down. This knowledge is important when producing precise five-axis milled workpieces. Nevertheless there is a positive aspect observed. When changing the axis speeds with cutting lubricant some thermal location errors are damped as it can be seen in Figure 11.

6 FURTHER STEPS

In the current extended physical compensation model the environmental temperature change is not included due to the size of the model. If a physical compensation model for environmental temperature variation error (ETVE) has to be developed a detailed model of the whole machine tool needs to be built [9]. The lack of geometrical data prevents from making a detailed physical compensation model for ETVE. Therefore a phenomenological model is developed that allows compensating ETVE as well as thermal errors induced by the rotary and swiveling axis unit of the machine tool. In a further step it is planned to extend the model by compensating thermal errors caused by rotating the main spindle. The phenomenological model requires just measurements of the environmental conditions (inside and outside temperature, hall door position, etc.). All other input parameters can be read out of the machine tool control As mentioned thermal error measurements often require expensive equipment. Therefore a compensation procedure is developed compensating thermally errors induced by running the rotary and swiveling axis unit of the machine tool using the 3D touch probe system of the machine tool. It will be investigated, whether the 3D touch probe system can be used for compensating thermal errors of machine tools. It is started with a precise phenomenological modelling of the NMV 5000 DGC for compensating thermal effects. The model enables a better representation of environmental impacts to TCP-errors. Further the approach is used to model cutting lubricant influences. The phenomenological error model of the NMV 5000 DCG is extended by the influences of the cutting lubricant.

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