Measurement and Simulation of Cutting Process Influence on Machine Tools Thermal Behaviour

J. Hornych, M. Mareš, O. Horejš
Research Center of Manufacturing Technology at Czech Technical University in Prague, Czech Republic (RCMT)

Abstract

The thermal behaviour of machine tools is important influence affecting final manufacturing accuracy and it can cause more then 50% of overall dimensional inaccuracy of workpieces [1]. Application of software algorithms is the most frequent remedy applied to eliminate the thermally induced errors. Currently, the compensation of thermally induced errors is performed by real time simulation algorithms, including thermal load produced by internal heat sources such as spindle units or ball screw feed drive systems. This fact applies to ordinary polynomial algorithms as well as to advanced real time simulations. However, most of these simulations neglect a very important and hard-to-define thermo-mechanical factor (which is a more appropriate term than a heat source), namely the cutting process. Compared to the research effort on measurement, simulation and compensation strategies related to thermal errors, the influence of the machining process and the influence of the coolant have not been studied with the same intensity [3]. Hence the article deals with the cutting process, which (in terms of thermal behaviour) affects machine tool accuracy markedly and in several ways.

1 Thermo-mechanical influence of cutting process

1.1 Current loading of a spindle

First, the cutting process causes current load growth in a spindle motor winding, which leads to the growth of thermal losses when torque increases during cutting. The main issue is the temperature rise of the spindle rotor because, contrary to spindle stator, direct cooling of this part is not usual for common spindles. Despite the above mentioned facts, the thermo-mechanical influence of a spindle unit is typically identified by the thermal dissipation of bearings measured during air cutting (i.e. rotating the spindle with no chip removal). On that account the spindle thermal probe is placed near the front spindle bearing assembly. Though current load changes according to the rotational speed of a spindle (Table 1 shows speed-current characteristic during air cutting), the situation could be completely different when a spindle works in a real machining process.

For example, mean current/A = 9.06 (see the last row of Table1) achieved at maximum rotational speed was just circa 25% of the maximum mean current of the spindle. Moreover, rough cutting could cause more intense current loading during lower rotation speed when bearing thermal dissipation is also lower. The air cutting based simulation model cannot work properly in such a situation while rotational speed is low and current loading is high. Therefore neglecting current loading evidently causes unacceptable inaccuracies in the simulation if the current load produced by the cutting process reaches a certain point (see more in chapter 2).

Table 1: Air cutting speed-current characteristic of Kessler LC 200 spindle

Rotational speed/rpm	Mean current/A
100	0.66
1000	1.04
3000	1.00
6000	3.30
9000	6.14
11000	8.40
12000	9.06

1.2 Heat from a cutting area

The second issue is cutting heat which is removed from the cutting area via chips, a workpiece and a cutting tool. A part of this cutting heat could be also removed by using cutting fluid. The mutual ratio of the mentioned cutting heat fluxes as well as the total amount of the heat produced depends on actual technological conditions and the rate of tool wear. A rough estimate of the total amount of the heat produced could be obtained with the help of auxiliary technological applications for setting up technological conditions. Nevertheless, there are no utilities available to approximate the heat fluxes ratio [5].

The heating of a workpiece, as well as heating of a tool, causes them to dilate, which is of course an undesirable effect contributing to the increase in the total thermal error. However, another hard-to-describe factor is the influence of the mentioned heated parts on the overall thermal behaviour of the machine tool structure. The tool heat flux is directed against the spindle rotor heat flux, which adds to the complexity of the already described thermo-mechanical spindle difficulties. The situation could be similar in the case of workpiece heat flux when some feed drives and position measurement are located under the workpiece table.

A very important factor is the above mentioned utilization of process cooling. Cooling is important for all thermal errors of the manufacturing process if it is applied. However, process cooling increases the price of manufacturing so there has been an effort to use dry cutting. When dry cutting is used, secondary heat flux from hot chips should be taken into account as no chip removal is so fast and excellent as required. The relevance of the influence of chip depends on many variables which are often mutually linked. The essential value is the starting temperature of the chips immediately after cut-off. However, the temperature of the chip in the place of chip fall is more important. The temperature of the fallen-off chip (besides the mentioned cut-off temperature) depends on the chip shape, weight, speed of chip movement after cut-off, length of trajectory and workspace air temperature. The tendency of the chip to wind up and its ability to accumulate as well as the site where hot chips tend to accumulate are factors which are hard to quantify. It is not easy to determine the density, specific thermal capacity and thermal conductivity of objects formed from accumulated chips as they comprise of air and metal. The same applies to thermal conductivity between the object of the chip and another surface (workpiece, machine tool frame). Another objective that has not been solved yet is the determination of the point when certain amount of particular hot chips should be considered as the above mentioned object with its own physical properties.

Figure 1: Machine tool used for experiments

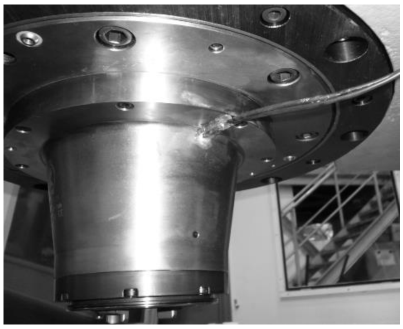

Figure 2: Placement of spindle thermal probe

1.3 Convective boundary condition

A convective boundary condition and its changes should be also taken into account. It is a well-known fact that changes in air flow velocity and directions in the vicinity of a machine affect courses of thermal deformations markedly even if the changes are slight. It is possible to ensure stable surroundings for machine tool operation although it may be expensive. But within the machine tool workspace, especially if the workspace is covered, the value of the heat transfer coefficient changes significantly when the tool starts cutting and the assumption of free convection is not correct in certain parts of the surface (surface of the machine tool frame and surface of the workpiece). Nevertheless, the measurement of the heat transfer coefficient value is not easy for several reasons.

A considerable range of air flow speed values within the workspace adds a complication to sensor selection. Different sorts of sensors are appropriate for low speeds and vice versa. Design of some sensors is not robust, which, in combination with high costs of these probes and demanding conditions during cutting process, could prove problematic. Finally, measured values are valid for immediate surroundings of particular probes. Therefore, their proper placement is very important considering the limited number of those probes. Thus, the determination of the array of heat transfer coefficient values is a weak point of the thermally induced errors simulations.

2 Identification and simulation of cutting process thermo-mechanical Influence

2.1 Cutting process thermo-mechanical influence measurement

In order to implement the cutting process influence into the existing simulation models based on transfer functions, a series of measurements was planned. For the time being an introductory, and to a certain degree experimental, series of technological tests was run. A three axis machine tool (see Fig. 1) equipped with the LC 200 Kessler spindle (see Table 1) was used for technological experiments. The frame and feed drive parts were fitted with many temperature sensors. Temperature of the front spindle bearing assembly was also measured (see Fig. 2). Face milling was chosen as the basis of measurement of cutting process influence. The experiments started with a 7 edge milling cutter but due to frequent colisions it was exchanged for a 5 edge cutter (see Fig.5). Standard steel was applied as the workpiece to ensure repeability of the cutting conditions for the following experiments. Thermal deformation was measured using a stylus of a workpiece probe. The stylus touched an edged small prism placed in front of the workpiece (see Fig. 3).

Figure 3: deformation measurement (edged small prism-right down corner)

Besides temperatures and thermal deformations, important machine tool parameters, such as current load, running speed, etc., were measured during the tests. As a new parameter the thermal field of the workpiece and tool were measured using an infrared sensor (see Fig. 4) and an infrared camera. The infrared sensor was aimed at the upper part of the tool (see Fig. 5).

Figure 4: Used infrared sensor for the tool temperature measurement

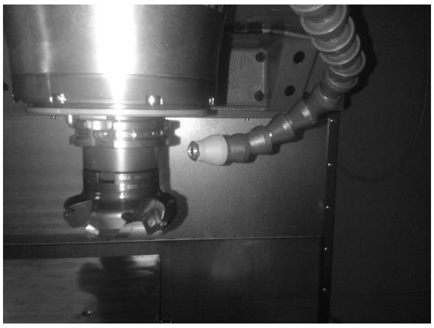

Figure 5: Used 5 edge cutter and the infrared sensor placement

An experimental measurement of the value of the heat transfer coefficient was also performed in the workspace. The heat transfer coefficient sensors were magnetically fixed in the workspace (see Fig.6) and on the outer surface of the machine tool in order to compare workspace and outer convective boundary conditions.

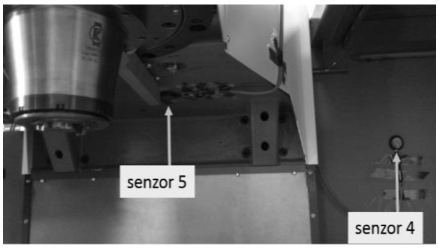

Figure 6: Heat transfer coefficient sensors placement in the workspace

Figure 7: The detail of used heat transfer coefficient sensor

2.2 Measurement results and results of cutting process thermo-mechanical influence simulation

All followed figures and text concern just the Z direction of the tested machine tool because the Z axis showed worst thermal behaviour manifestation.

An schema and describtion of the three axis machine tool along with placement of relevant thermal probes from an approximation model point of wiev (T_{spindle} placed close to spindle bearings, $T_{\text{feed drive X}}$ close to a nut of a ball screw of X axis feed drive, $T_{\text{feed drive Z}}$ is placed near to Z axis motor and T_{amb} for recording of changes in ambient temperature) are depicted in Figure 8.

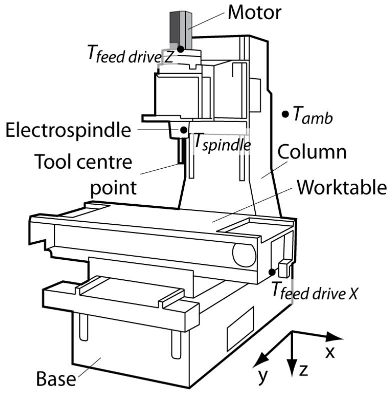

Figure 8: Three axis machine tool schema and relevant temperature probes placement

The aircutting approximation model based on thermal transfer functions (in short AC TF model) includes description of thermal influences caused by spindle rotation and the Y and Z axes movement (the latter is not relevant for now). Details of the AC TF model are discused in [2] and details of thermal transfer functions using are discused in [4].

The Figure 9 shows behaviours of inputs into AC TF model (4 abovementioned temperatures) during aircutting mode which was adjusted as 3kW cutting test.

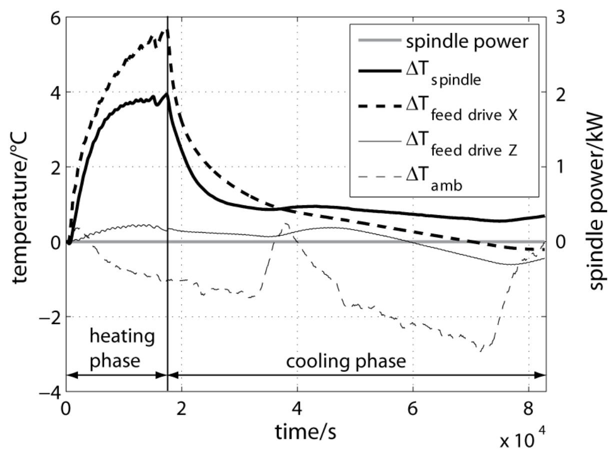

Figure 9: Inputs into the approximation model during aircutting test

The Figure 10 contains a comparison of measured thermal deformation in Z direction (black curve) with results of applied AC TF model (gray curve) during the aircutting mode. Let‘s note that the discussed AC TF model was calibrated during different aircutting tests [2]. A reduction of thermal errors achieved by using the approximation model is up to 79% in comparison with uncompensated state. Intensity of the cutting process impact upon aircutting base simulation is obvious from e.g. Figure 12.

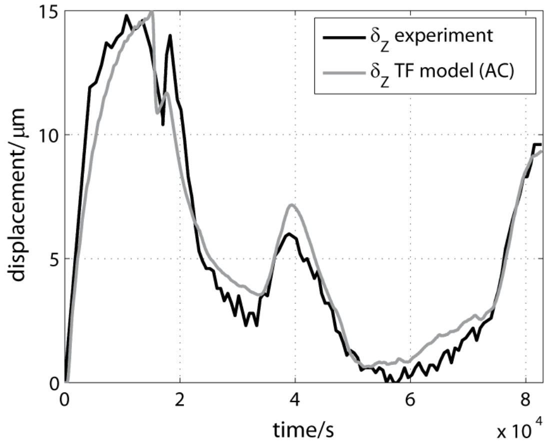

Figure 10: Thermal deformation of Z axis during aircutting (adjusted as 3kW cutting test) and results of simulation

Calibration of the cutting process influence was performed as follows:
(1) The TF AC model was applied on 3kW cutting test data (inputs into the model are depicted in Figure 11)
(2) The calculation of the residue between measured and simulated data (full thin black curve in Figure 12) is used as a response in an identification process of cutting influence. The record of spindle power was used as an excitation (see in Figure 11). The result of the identification is shown in Figure 12 by dashed thin black curve δ_z TF model (CP).
(3) Resultant approximation is calculated by superposition of aircutting influence and spindle power impact (dashed thick black curve in Figure 12).

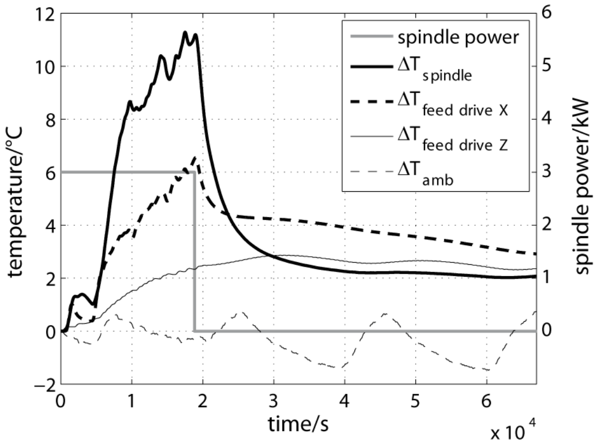

Figure 11: Inputs into the approximation model during 3kW cutting test (performed with 5 edge cutter)

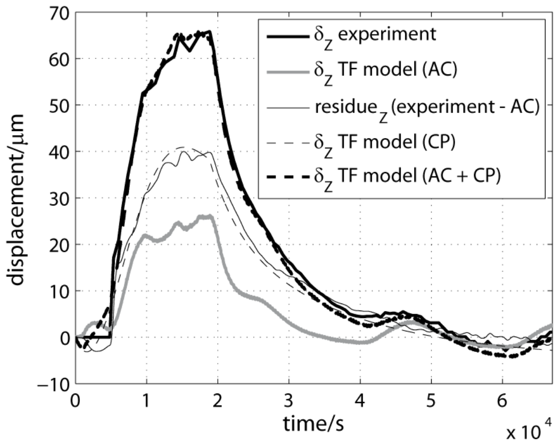

Figure 12: Thermal deformation of Z axis during 3kW cutting test (performed with 5 edge cutter) and results of simulations

Aplication of the identified TF model on 1.5kW cutting test is shown in Figure 13. A reduction of thermal errors achieved by using the new approximation model is up to 65%.

The second verification of the identified TF model was performed during 4.5kW cutting test. The results are shown in Figure 14. A reduction of thermal errors achieved by using the new approximation model is up to 70%

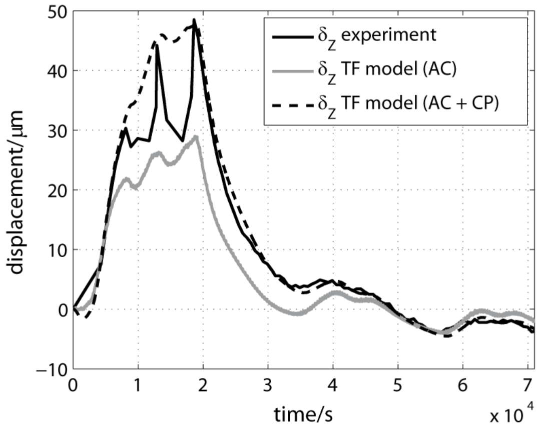

Figure 13: Thermal deformation of Z axis during 1.5 kW cutting test (performed with 5 edge cutter) and results of simulations

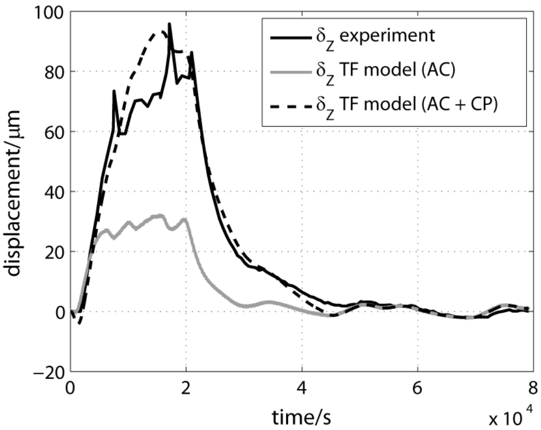

Figure 14: Thermal deformation of Z axis during 4.5 kW cutting test (performed with 5 edge cutter) and results of simulations

3 Conclusion

Inaccuracies of presented simulations were probably caused by temporary neglection of the changes of technological conditions (tool heat flux and its changeovers after tool exchange). It is possible to suppose higher inaccuracy in the event that different kind of tool would be used.

The convective boundary condition of workspace and its changes were also neglected. Although the experimental measurement of the value of the heat transfer coefficient was performed in the workspace, the data will be useful after an additional calibration of the sensors (calibration for low speeds of air flow).

All neglected values will be possible to take into account after a sensitivity analysis fulfilment but another series of measurements must be performed.

A new apparatus was developed for this measurements, namely two versions of spindle brake (see Fig. 15 and Fig. 16).

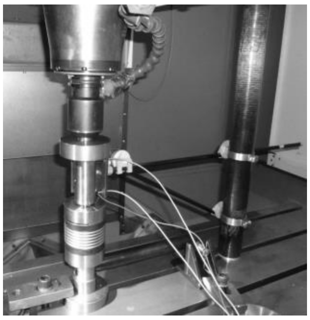

Figure 15: A static version of spindle brake

Figure 16: A dynamic version of spindle brake

In the near future this brakes will enable to measure the independent thermo-mechanical influence of the current load and tool rotation with no influence of cutting process. In combination with the results of the technological tests, it will be possible to evaluate the influence of individual heat sources and boundary convective changes on the resultant thermal error. However, despite the above mentioned inaccuracies, 70% of the errors are covered by the model applied.

4 Acknowledgements

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5 References

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