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The influence of coolant on the thermo-elastic machine tool behavior

Prof. Dr.-Ing. Christian Brecher[1] Dr.-Ing. Marcel Fey[1] Dipl.-Ing. Dipl.-Wirt. Ing. Matthias Wennemer[1]

[1]*laboratory of machine tools (WZL), RWTH Aachen*

m.wennemer@wzl.rwth-aachen.de

Abstract
Today, up to 75 % of the overall geometrical errors of machined workpieces can be induced by the effects of temperature. Concerning this, different external and internal heat sources and sinks were investigated but research findings which focus on the influence of coolant are hard to find. Therefore, a methodology to analyze the thermo-elastic behavior due to the influence of coolant is developed and applied on a 5-axis machine tool.

machine tool, thermo-elastic behavior, process heat, coolant

1. Introduction

In the field of machine tools the trend of energy efficient, fast and precise cutting processes is unbroken. Nowadays, the prediction of thermo-elastic machine behavior has a great impact. Up to 75 % of the overall geometrical errors of machined workpieces can be induced by the effects of temperature [1]. Internal and external heat sources and sinks induce a transient temperature distribution within the machine structure, which yields to a positioning inaccuracy of the Tool Center Point (TCP). In the past, the effects of internal heat sources, such as the heat waste of the driven parts like the main spindle and the linear axes as well as the external influences e.g. daily temperature fluctuations were investigated in detail [1–3]. The influence of coolant on the machine accuracy has hardly been investigated, although this could exert considerable effects on the machining result [4, 5]. Thus, the targeted use of the cooling lubricant offers great potential for increasing the machining accuracy.
In the following, a methodology to capture and analyze the thermo-elastic behavior under the influence of coolant is presented and applied to a 5-axis machine tool.

2. Measurement setup and procedure

The thermo-elastic behaviour due to the influence of coolant is exemplary investigated on a 5-axis machine tool with a rotary/ tilt table in CAFYXZ configuration. The direct linear drives of the x- and y-axes as well as the z-axis (driven by a ball screw drive) span a machining volume of 400x400x375 mm^3. The C-axis is also driven by a direct linear drive. The main spindle, all linear drives, the nut of the ball screw and the linear guides of the x- and y-axes are temperature controlled with a flow temperature of 24.5° C. The machine tool is exposed to ambient temperatures ranging from 19° C to 20.5° C. The machine tool is equipped with a usual dual-tank system of approximately 0.6 m^3 coolant (lubricant/ water mixture) which is not temperature controlled.

A test mandrel changed in the spindle and a fixture equipped with five linear displacement sensors placed in the centre of the C-axis allows for a measurement in accordance with ISO 230-3. The test mandrel and fixture is made of Alloy 36 with a thermal expansion coefficient of approximately 2 µm/(mK). This results in a measurement setup which is robust against a flooding for cooling lubricants. Otherwise, the thermo-elastic behavior of the measurement setup instead of such of the machine tool would be captured. The machine tool components are equipped with 50 temperature sensors in total. Furthermore, the ambient temperature is recorded at six different locations in four different heights around the machine (0.5 m, 1.0 m, 1.5 m, and 2.0 m). The spacing between ambient temperature and machine structure is approximately 0.5 m. Deviations and temperatures are recorded every minute.

The machine tool is switched to idle mode 24 h before each measurement to reach steady state and reduce effects of temperature other than the coolant. Measurements start at the same time each day for the purpose of maintaining comparability. This yields to a daily fluctuation in ambient temperature which is more or less the same for each measurement series. A measurement series consists of at least one heat-up and one cool-down stage. Both phases are associated with different thermo-elastic behavior (different time constant) due to changing heat sinks and sources.

Investigations on several scenarios were conducted. These could be reduced to only two measurement series left to reveal the major influence of coolant on the machine accuracy of the given machine tool. First measurement consists of one heat up and cool down stage until steady stage, whereby coolant is switched on (12 h) and off (12 h) as a thermal load. Second measurement includes a periodic test where coolant is switched on (30 min) and off (10 min) several times. The methodology to interpret the results is presented in the next chapter.

2. Interpretation of results

The interpretation of data captured during thermo-elastic displacement experiments requires a reduction methodology as there is a large volume of data as well as a lot of superimposing effects on one another. In a first step, a correlation analysis of the temperature and deviation values is conducted. This reveals the significant thermo-elastic behavior of the different machine components.

For this purpose, the temperature sensors are assigned to machine components. As a result of the correlation analysis, an upper triangular matrix of the size of input values reveals the general relationships (Figure 1). A colour overlay supports identification. Data amount is further reduced by calculating the average, the standard deviation and optionally the spread of the correlation coefficients of the single components. This reduces the upper right triangular matrix to the size of defined components. The first interpretation to reveal the homogeneity of the temperature distribution of each component as well as their similarity to each other can now be evaluated more quickly.

Homogeneous temperature courses over time yields to high homogenous absolute values of the correlation coefficients. Therefore, machine components influenced by a single heat source/ sink as a whole can be easily identified. They lead to even coloured boxes within the ordered matrix of correlation coefficients. This is often a sign for the influence of the ambient temperature because the whole structure has to be influenced. In the given example, the Y-axis is mainly influenced by the ambient temperature as there is a good isolation to the machine volume (Figure 1). Furthermore, interactions between different machine components can be identified. In summary a correlation analysis is a good choice to understand thermo-elastic behavior of machine tools more quickly.

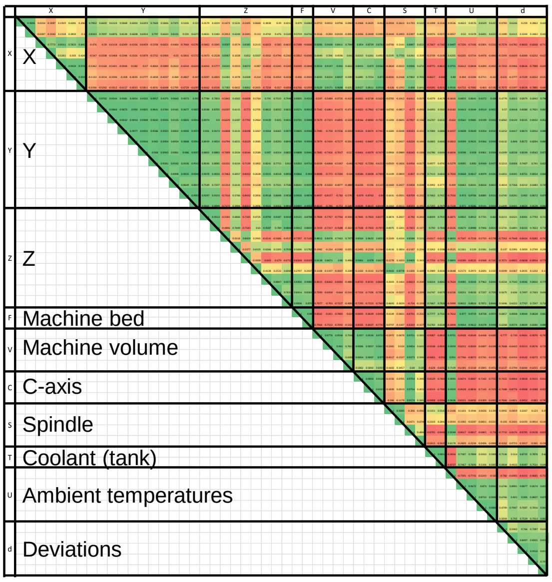

Figure 1. Example of an upper triangular matrix of correlation coefficients

Last, a detailed analysis of single temperature and deviation measurements has to be conducted. The correlation analysis will help to find relevant temperature curves. The interpretation should be conducted in accordance with ISO 230-3. As a result, the ranges to steady state as well as the ranges within the first minutes are known. A fitting algorithm of first order time delay elements described by gain, time constant and time delay can be used to describe these curves more in detail. This can be done semi-automatic [6].

The main findings concerning the influence of coolant on the machining accuracy are illustrated in the next chapter.

3. Exemplary results on the influence of coolant

The active machine components are tempered at 24.5° C while the ambient as well as the coolant has a temperature of approx. 20° C (at the beginning). Thus, the active machine parts like the C-axis are cooled down while the coolant itself is heating up. The further the distance between machine components and machine volume (Machine bed), the stronger is the influence of the ambient rather than the coolant. Time to steady state (90 % of steady state value) ranges from 10 min (spindle) to over 2 hours (e.g. X- and C-axis) depending on mass and mass distribution. This leads to particularly transient thermo-elastic temperature courses and finally deviations up to 20 µm. Additionally, the different temperature conditions lead to temperature gradients affecting machine accuracy negatively.

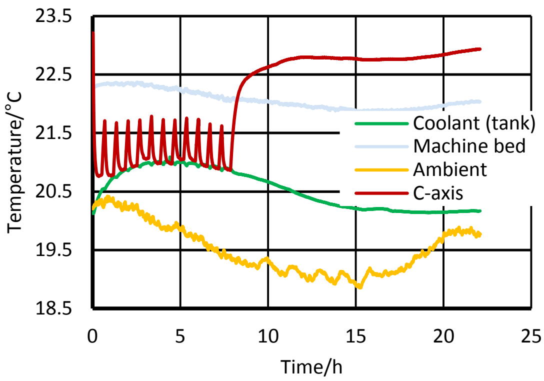

Figure 2. Representative temperature courses of the second measurement

4. Summary and outlook

The influence of coolant on the machine accuracy has hardly been investigated. Therefore, a measurement setup and procedure as well as a methodology to interpret the results are shown from the example of a 5-axis machine tool. In summary, coolant can have a major impact on machining accuracy and therefore should be investigated in more detail. Further work will concentrate on the optimal temperature control of coolant to reach more stable machine states.

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