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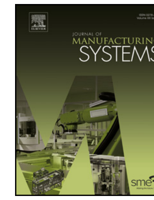

Technical Paper

Thermal error compensation of rotary axes and main spindles using cooling power as input parameter

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ABSTRACT

Thermal errors of machine tools are one of the main contributors for geometrical inaccuracies of machined workpieces. In this paper, research work is presented compensating thermal errors induced by moving the rotary and swiveling axis unit of a five axis machine tool as well as running the main spindle. The compensation approach is based on a dynamic gray box model consisting of a system of differential equations. Input parameters related to the generated heat are investigated. The best relation between the arising thermal location errors and model input parameter is found for the cooling power of the machine tool axes and the main spindle. Based on measurements it is shown that all dominant thermal location errors can be significantly reduced.

1. Introduction

Due to increased demand of geometrical accuracy of five-axis machined workpieces in the recent years, machine tools with rotary axis became more important for precision applications. Thermal influences are one of the major errors sources and cause up to 75% of the geometrical errors of workpieces [17]. Bryan [2] summarized in the "Thermal Effects Diagram" the mechanism leading to thermal errors of workpieces. The sources of thermal errors mentioned here are:

- Heating or cooling influences by the room environment
- Heating or cooling influences by coolants
- Effects of people
- Heat generated by the machine
- Heat generated by the (cutting) process
- Thermal memory from a previous environment

Neglecting the influence of the process and the people, research focused for a long time on regarding thermally caused deviations due to the influences of the environmental temperature change, the main spindle, and the linear axes [10,12,13]. In newer research the thermally induced location errors of rotary and swiveling axes of five-axis machine tools have been investigated [4,8,9]. Several compensation models have been developed to reduce the thermal errors arising when running the machine tools [1,17]. Gebhardt et al. [6] use a gray box model to compensate thermal errors of five-axis machine tools consisting of a system of differential equations.

2. Machine tool under investigation

The machine tool under investigation is a five-axis vertical milling machine. Fig. 1 illustrates schematically the kinematic structure of the milling machine and the used measurement devices. The swiveling axis B and the rotary axis C are serial arranged on workpiece side. The kinematic chain of the vertical machine tool can be described in accordance with ISO/DIS 10791-1.2:2013-07-12 [14] as:

V [w C2' B' b [Y1 Y2] X [Z1 Z2] (C1) t]

The C-axis of the machine tool can be used in turning mode with a maximum speed of S = 1200 rpm. The maximum speed of the swiveling axis B is 50 rpm. Both axes can be positioned with a resolution of 0.001°. The gantry axis Y, the X-axis and the gantry axis Z are serial arranged on the tool side. The NC-setpoint resolution of the linear axes is 1 μm. The motor spindle (C1) of the machine tool is not an interpolating NC-axis. The axis can be positioned in one axis position only. The maximum speed of the main spindle is S = 12000 rpm.

The machine tool has two separate internal cooling circuits. One circuit is tempering the rotary and swiveling axis unit. The inlet coolant stream is separated in the coolant stream for the rotary

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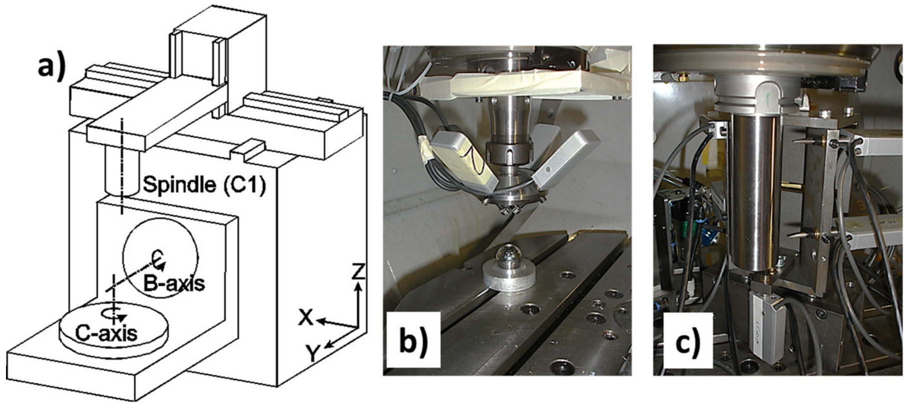

Fig. 1. (a) Kinematic (schematic) of the machine tool under investigation [3]; (b) R-Test measuring device; (c) "ISO setup" according [10].

axis and the one for the swiveling axis. Each axis is supplied by 50% of the coolant stream of 21.85 l/min. The coolant used for the rotary/swiveling axis unit is oil. In Table 1 the heat related material parameters of the oil are given.

The second cooling circuit for the main spindle and linear axis ball screw units uses the same type of oil as coolant. The coolant stream of 20.21 l/min first flows through the main spindle and afterwards through the ball screws of the machine tool. The outlet volume flow of the spindle is separated in a distribution unit for the ball screws. Each ball screw is supplied separately. The coolant flow distribution to the ball screws is not investigated. The outlet flows of the ball screws are collected in the distribution unit. Both cooling cycles have an equal chiller unit with a maximum cooling power of 3.8 kW each.

The coolant outlet temperatures (= flow into the chiller units) of the cooling units are controlled according to the bed temperature of the machine tool. In [5] a model to compute the inlet temperature (= flow out of the chiller units) of the B-/C-axis coolant stream is presented. The inlet temperature depends on the axes power consumption of the B-axis, P_B, and C-axis, P_C, only.

3. Measuring the thermally induced errors

Three different measurement setups are used for investigating the thermal errors depending on moving the rotary axis, swiveling axis and main spindle. For investigations of the C-axis and a combined movement of the B- and C-axis a discrete R-Test setup [18] is used. For measuring the thermal errors induced by movements of the B-axis only, the continuous R-Test [18] setup is also used. For investigation of thermal errors arising by running the main spindle a test setup according to [10] is used.

3.1. R-Test discrete

The discrete R-Test is used for evaluating the thermally induced errors of the rotary axis C. In Table 2 the thermally induced location errors of a vertical rotary axis C are listed. The errors indicated in bold letters are errors to be compensated. Due to the symmetric structure of the machine tool some errors arising are lower than the correction value resolution of the machine tools linear axes of 1 μm and can therefore not be compensated. The errors are denominated according to [11]. In addition to the errors of rotary axis mentioned in ISO 230-7, for geometrical errors only, two further errors must be taken into account when investigating the thermal behavior. The axial positioning error of the table surface in Z-direction, E_{Z0T}, and the radius error of the table, E_{R0T} [3].

A description of the discrete R-Test discrete measurement cycle is given in [7,16]. Basically a set of positions on the circumference of a X-Y-C-interpolation is measured to derive the location errors. In this case here, the thermal displacements between the sensors, clamped in spindle, and the precision sphere, mounted on the table, is measured in three axis directions in four axes positions. The table is rotated between the measurement positions by 90°. For the measurements the axes X, Y, Z, and C have to be interpolated. The axis B and the main spindle are clamped mechanically during the test. When evaluating a combined B- and C-axis movement with the discrete R-Test setup the axis B is positioned during the measurements and not clamped mechanically. The form deviation of the sphere is less than 0.1 μm. The measurement uncertainty of the setup is given in [18] with $U(k=2) = 1.7$ μm.

3.2. R-Test continuous

In [15] the uncertainties in computing index circles in coordinate measuring is described. The uncertainty depends, besides the accuracy of the measurement device, mainly on the number of measuring points and the angular size of the segment of the probing point around the circle that is measured. Investigating the horizontal swiveling axis B the thermally induced displacements cannot be measured in four axes positions, while each axes position is changed by 90° of the B-axis. On the one hand the axis can just be positioned between −180° and +160° and on the other hand there is a collision of the B-axis corpus and the sphere holder clamped in the main spindle. The maximum measuring angle is 155°. Using the continuous R-Test setup the sphere clamped in the main

Table 1
Heat related material parameters of the coolant oil.

Material parameter	Unit	Value
Density (ρ)	$\frac{kg}{m^3}$	815.3
Heat capacity (c_p)	$\frac{J}{kg\,K}$	1942

Table 2
Overview of thermally induced location errors of the vertical rotary axis C analyzed in this paper; bold indicates errors which are compensated; notation according to [9].

Thermally induced location errors of a vertical C-axis		
Error	Unit	Description of the error
E_{X0C}	μm	Position error of C in X-axis direction
$\mathbf{E_{Y0C}}$	**μm**	**Position error of C in Y-axis direction**
$\mathbf{E_{Z0T}}$	**μm**	**Position error of the table surface in Z-axis direction**
E_{A0C}	μm/m	Orientation error of C in A-direction; squareness of C to Y
E_{B0C}	μm/m	Orientation error of C in B-direction; squareness of C to X
E_{C0C}	μm/m	Zero angle error of the C-axis
$\mathbf{E_{R0T}}$	**μm/m**	**Radius error of the table**