Thermal behaviour of machine tool spindle

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ABSTRACT

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The thermomechanical deformation of machine tools, caused by external and internal heat sources, is one of the main contributors to the overall geometric error of the workpiece. In order to reduce the errors on machine tools which are caused by thermal deformation, it is important to understand the influencing factors. The Machine tool spindles are the most predominant part which is getting affected more by external and internal heat sources. This document describes the method for efficient quantitative estimation of the thermal characteristics of the spindle unit in accordance with ISO 230–3 standard. The method of measurement, and measurement conditions and applicable standards reference to relevant Standards are presented for the benefit of the manufacturers and user of machine tools. The tests described in this document are not mandatory, and to be considered for machine acceptance, if agreed between buyer and seller.

1. Introduction

Thermally induced displacements at the tool center point (TCP) of a machine tool (MT) structure cannot be sufficiently reduced by design concept and/or by temperature control without high additional costs. On the contrary, indirect (software) compensation of thermally induced displacements at the TCP is one of the most widely employed techniques to reduce Machine Tool thermal errors due to its cost-effectiveness and ease of implementation. This document describes a method for efficient quantitative estimation of the tool center point (TCP) deflection due to external and Internal heat sources (Fig-1).

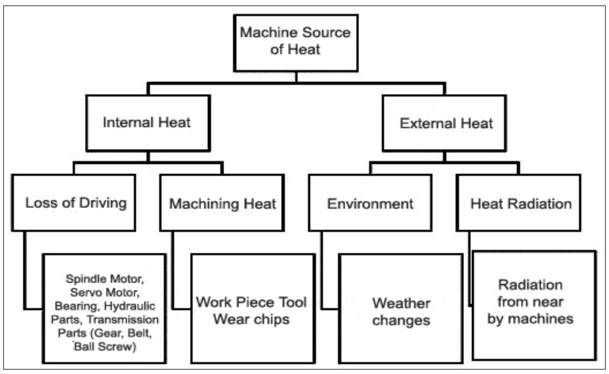

Fig. 1. Sources of heat in machine.

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Tool Center Point (TCP) shift because of change in ambient temperature and spindle thermal behaviour can be studied. The component accuracy variation due to TCP shift can be predicted, using this measurement.

The TCP shift is established by measurements carried out under the following two variables:

a) ETVE (Environmental Temperature Variation Error) Test

b) Thermal distortion caused by rotating spindle.

2. Machine Installation

- The machine shall be completely assembled, levelled and clamped/grouted on a suitable foundation, fully operational in accordance with manufacturer's instructions, geometric alignments and functional checks completed before starting the calibration.
- The machine shall be powered up with auxiliary services operating and axes in the "Hold" position, with no spindle rotation, for a period sufficient to stabilize the effects of internal heat sources as specified by the supplier/manufacturer or as indicated by the test instrumentation.
- The machine and the measuring instruments shall be protected from draughts and external

radiation such as those from overhead heaters or sunlight.

- All measurements shall be carried out with the machine in the unloaded condition, i.e. without a workpiece.
- Machine and the measuring system should be connected through proper earth.

3. Environment Conditions

- The environment temperature as suggested by the manufacturer to be maintained during the measurements.
- If the measurements are taken at ambient temperature other than 20°C, then the correction for nominal differential expansion between the axis positioning system and the representative part machine tool body (machine table) shall be applied to yield results corrected to 20°C.

4. Measurement Setup

The details of measurement set-up are indicated in Fig. 2, Fig. 3a and Fig. 3b.

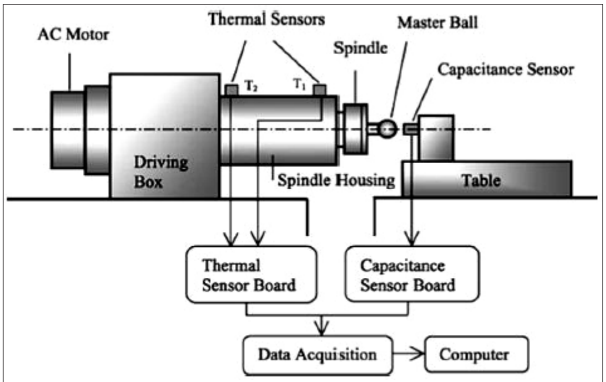


Fig. 2. Measurement set-up.

Thermal displacement measurement setup consists of Test Mandrel (Master ball Target), Test fixture (Probe Nest), Linear Displacement non-contact sensors (Inductive or Capacitive type), Air temperature sensor and Material temperature sensor (e.g. thermocouple, resistance or semiconductor thermometer), Data acquisition equipment (DAQ), Display unit (and/or) Computer,

- Data acquisition equipment (DAQ), such as a multi-channel chart recorder which continuously monitors and plots all channels, or a computer-based system in which all channels are sampled at least once every 5 min and data is stored for subsequent analysis;
- Test mandrel (Master ball Target), preferably made of steel, with the design specified in ISO 230-1. Fixture (Probe Nest) to mount the non-contact displacement sensors, preferably made of steel, with the design specified in ISO 230-1, which should minimize local distortions caused by temperature gradients in the fixture.

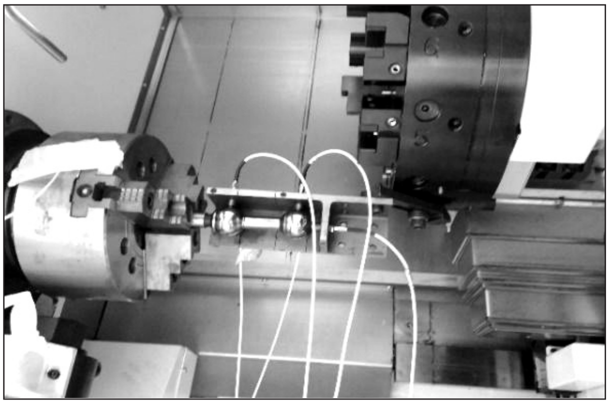


Fig. 3a. Thermal distortion set-up for measurement setup on turning machine.

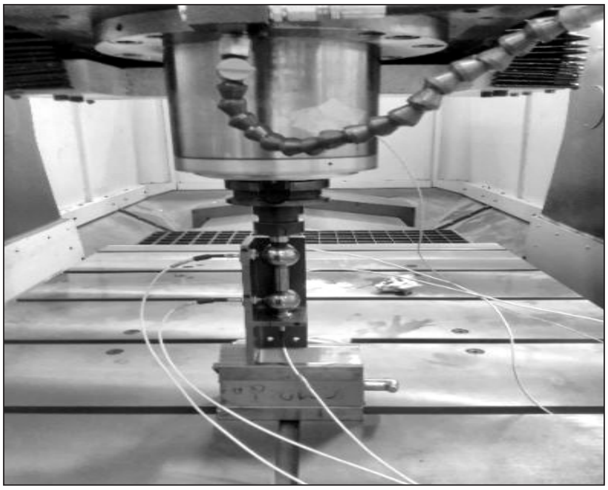


Fig. 3b. Thermal distortion set-up for measurement setup on milling machine.

- Material temperature sensor need to be placed near the hear generating sources and machine structures, in order to find the heat distribution of the machine. The general arrangement for the temperature sensors is shown in Fig. 4.
- The fixture in which the linear displacement sensors are mounted shall be securely fixed to the non-rotating work holding or tool-holding zone of the machine (Ref Fig. 5) so as to measure the relative displacements between tool and the workpiece along the

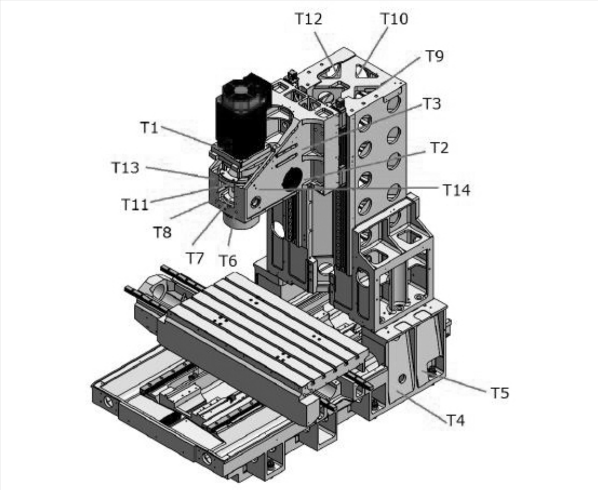


Fig. 4. Temperature sensor location on the milling machine structure.

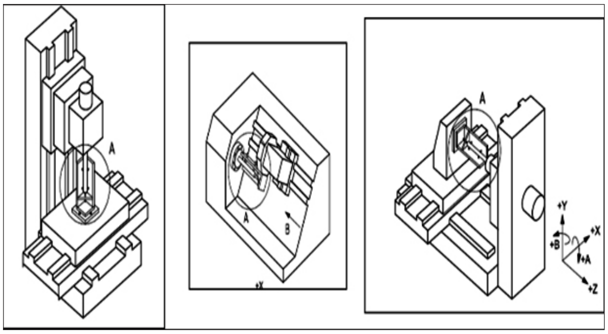


Fig. 5. Typical measurement set-up for a vertical and horizontal machining centre and a turning centre.

three orthogonal axes parallel to the machine axes, the tilt or rotation around the X and Y axes of the machine. The exact position of the measurement set-up shall be recorded along with the test results.

- The temperature of the machine structure — as close as possible to the front spindle bearing and the ambient air temperature in the close vicinity of the machine (if the machine is enclosed, then the temperature sensor should be placed outside this enclosure) and at the same height as the spindle nose, should be monitored at least once every 5 min. It is important to measure the ambient (environmental) air temperature at a suitable distance from the machine to avoid any influence by the heating up of the machine (for example by hydraulic components) on the ambient air temperature.

- The location of the non-contact sensors on a machining centre is to be maintained as indicated in Fig. 6a & 6b.

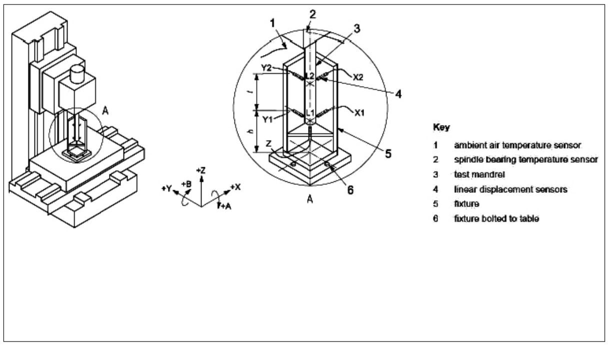


Fig. 6a. Machining center measurement setup with sensor identification.

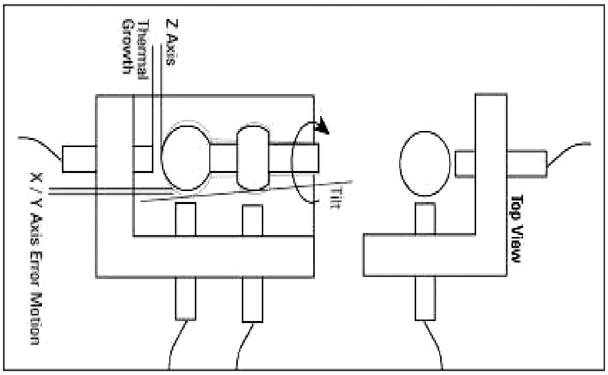


Fig. 6b. Sensors identification on fixture.

a) X1, Y1, and Z sensor output values define the thermal distortion along the corresponding (X, Y, Z) direction of the machine axes, and also the growth direction. Growth direction (+ sign indicate the increase in gap between tool and work piece) will specify the direction of spindle axis movement (whether spindle is moving towards the workpiece / away from the work piece),

b) X1, X2 sensor output will provide information about the tilt along X-direction. The Tilt (X) is calculated as (X1-X2)/L. If X1=X2, it implies that there is no tilt, which means spindle axis shift is parallel to X-axis).
Similarly, Y1, Y2 sensor output will provide the information about the tilt in Y-direction. The Tilt (Y) along Y-direction is calculated as (Y1-Y2)/L
Where, L- Distance between two sensors.

5. Presentation of Results

The following information should also be reported with the results of the test

a) Control mode for machine axis (hold or OFF).
b) Direction of deviations in X, Y, Z, A, B (same as machine coordinate system).

c) Location of the measurement set-up (coordinates of axes position).
d) Distance between spindle face and fixture.
e) Locations of temperature sensors.
f) Displacement sensors (Make and Resolution).
g) Material of the Test mandrel and Fixture.
h) Thermal compensation procedures on the machine.
i) Time and date of the test.
J) Machine preparation procedure prior to testing (time period for operating auxiliary systems).

6. Reference Standards

- ISO 230-3:2007 Determination of thermal effects.
- ISO 10791-10:2007 Evaluation of Thermal distorsions- Machining centers
- ISO 13041-8:2004 Evaluation of Thermal distorsions- Turning machine.

7. ETVE test (Environmental Temperature Variation Error)

Externally generated heat is produced from changes in environment temperature around the machine. This could be from an environment/ ambient temperature fluctuation throughout the day, the opening and closing of workshop doors, workshop heating system or heat generated by other machines in the close vicinity. The change in ambient temperature will lead thermal distortion at TCP. ISO 230-3 describe the ETVE (Environmental Temperature Variation Error) test method to quantitatively estimate the effect of Environmental variation on machine TCP.

7.1. Measurement procedure

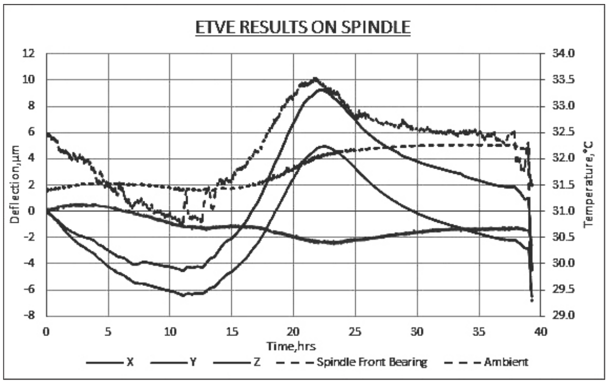
The ETVE (Environmental Temperature Variation Error) test, which is a drift test, is used to designate the effects of varying environmental temperatures on the positioning accuracy of the machine tool. It can also be used to estimate the thermally induced error during other measurements, whenever the environmental temperature is not constant. If possible, the temperature should be controlled according to the environmental temperature changes which are considered being acceptable to keep sufficient accuracy or according to the environment of the shop floor, where the machine will be installed.

Most of the CNC machines are being used at shop floor (Varying ambient) environment. The change in ambient temperature will affect the machine structure and lead to inaccurate machining. That's why component which requires high accuracies are being machined at controlled environment. This Environmental Variation error can be measured as per standard ISO test procedure.

7.2. Test condition and duration

This ETVE thermal drift test should be continued as long as possible or at least for one cycle of duration of 24hr (one day and one night), with a minimum deviation from normal performance measurement conditions.

An example of ETVE test carried out on the machine is presented below for the information. In addition, a graphical presentation of the results should be provided as specified in ISO 230-3 (Example Ref: Fig. 7)



PARAMETER	ETVE, (µm, °C)/60 Min
$ETVE_{X1}$	(1.8 µm, 4°)/ between 18-19hr
$ETVE_{Y1}$	(0.4 µm, 3°)/ between 19-20hr
$ETVE_{Z1}$	(2.3 µm, 3.5°)/ between 17-18hr

Fig. 7. Representation of EVTV test results.

8. Thermal Distortion Caused By Rotating Spindle

Internally generated heat is produced from the rotating elements within the spindle assembly such as, bearings, motors and gears, where high friction causes a temperature increase of the components.

This generated heat will flow through the spindle and machine structure causing thermal expansion and resulting in distortion between tool and work-piece at Tool Center Point (TCP). ISO 230-3 describes the measurement method to quantitatively estimate the effect of thermal distortion caused by rotating spindle,

This test is carried out to identify the effects of the internal heat generated by rotation of the spindle and the resultant temperature gradient along the structure on the distortion of the machine structure observed between the workpiece and the tool. Since it is related to the heat generation by the spindle, this test is carried out on machines with rotating spindles only.

The results of this test can be used to determine the Machine Warm up Period, the bearing temperature stabilization time, the direction of Spindle Thermal Growth (Whether it is towards the spindle / away from the spindle), and Spindle Thermal Stabilization time at different speeds and the optimum setting Spindle chiller unit temperature.

8.1. Measurement procedure

The test procedure should follow one or the other of the following two spindle speed regimes:

- *Variable speed spectrum*
- *Constant speed as a percentage af maximum speed*

The choice of the test procedure with spindle speed spectrum and the percentages shall be specified in machine-specific standards. If necessary, the supplier/manufacturer and user may agree on a different, special test schedule (e.g. a certain warm-up cycle before the test) corresponding to particular requirements. The spindle speed spectrums selected generally reflect practical usage of the machine tool.

The effect of test mandrel runout should be eliminated during the tests, when the spindle is rotating.

For example, for machining centres, a spindle speed spectrum consisting of different spindle speeds over 2min to 30min for each spindle speed, with periodic stops of 1min to 30min in between may be selected to represent typical machining conditions.

8.2. Test condition and duration

All transducer outputs (thermal drift) shall be monitored for a period of 4hr, followed by spindle stop condition for 1hr. During the spindle stopped condition of 1hr, the sensor output (thermal drift) monitoring is continued.

Alternatively, the measurement period is allowed until the thermal drift during the last 60min is less than 15% of the maximum thermal drift registered over the first 1hr of the test.

The measurement results should be plotted in graphs of thermal distortion/drift and temperatures (ambient and spindle bearing temperatures) versus time, as shown in the example illustrated below.

The effects of warming up the machine structure on the ability of the machine to maintain the position of the tool relative to the workpiece can be assessed from such graphs.

It should be noted that the starting and stopping of the spindle can cause offsets in the plots due to the effect of test mandrel runout. These effects should be ignored during the evaluation of thermal deflection.

An example of Spindle Thermal stability test carried out on the machine is presented below for the information. In addition, a graphical presentation of the results should be provided as specified in ISO 230-3.

8.2.1. Variable speed spectrum

The ISO recommended test condition for the variable speed spectrum is shown in Fig. 8 and the sample test result shown in Fig. 9.

The Variable speed spectrum results are also tabulated after 60 and 240-min, as indicated in Table 1.

Note: It is not mandatory to follow this specified test spectrum, Speed spectrum can also be decided based on actual working condition.

8.2.2. Constant speed as a percentage af maximum speed

The ISO recommends test condition as 3 - min Spindle running at 70% maximum speed followed by 1 - min Stop (Example Ref. Fig. 10)

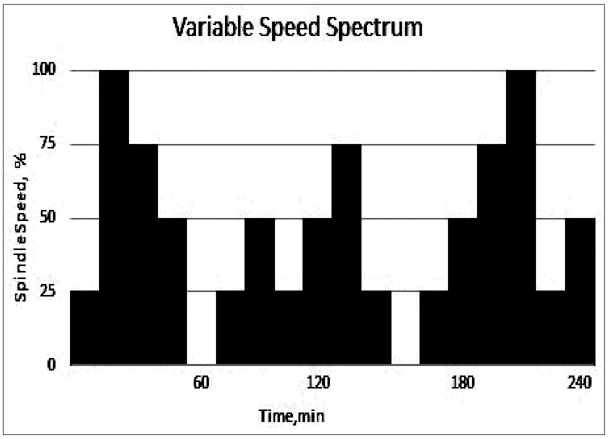


Fig. 8. Variable speed spectrum.

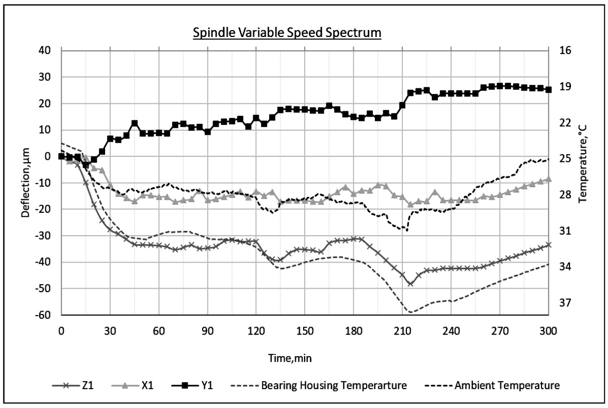


Fig. 9. Representation of results (variable speed spectrum).

Table 1
Variable speed spectrum results are also tabulated after 60 and 240-min.

Parameter	After 60 min, µm	15% of 60 min, µm	After End of Period (240 min), µm	Remarks
X1	11.5	1.7	19.6	•X-direction growth not stabilized.
Y1	-13.2	-2.0	-20.3	•Y-direction growth stabilized after 180min.
Z	52.06	7.9	72.6	•Z-direction growth stabilized after 75min.

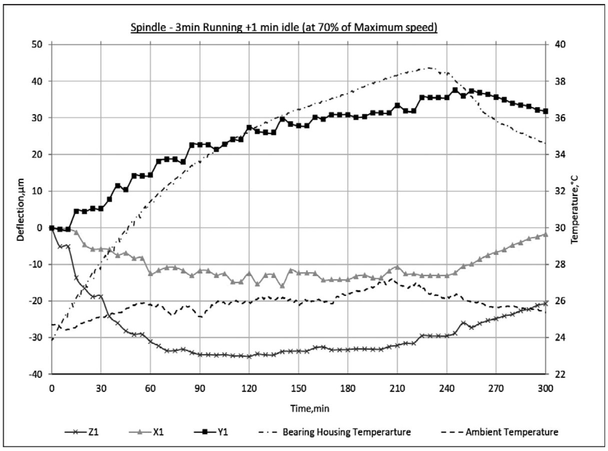


Fig. 10. Representation of results (spindle start and stop).

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Y Balaramaiah, Director, Advanced Machine Tool Testing Facility (AMTTF), AMTTF established with the support by Govt. of India, IMTMA and CMTI, and equipped with all the latest test facilities for Testing, Trouble-shooting and Problem-solving for Machine Tools and Engineering Industries. As Director-AMTTF, he is serving manufacturing industry for the last seven years to improve their product quality, and implementation of test methods and protocols as per relevant BIS/ ISO standards. He is a Post-graduate in Design and Production of Machine Tools from Regional Engineering College (NIT), Warangal. He has more than 40 years of experience in Machine Tool Testing, Assembly, Design and Manufacturing Engineering. He Specialized in Testing of machine tools performance as per National and International standards, improving performance and productivity of machine tools. Testing, Preparation of test protocols with acceptance criteria for performance evaluation of CNC machines, where the relevant Standards are not available. He represents IMTMA as member of BIS Sectional Committees PGD-35 (Machine tools, Machine tool elements and Holding devices) and MED-40 (Manufacturing machinery and their safety). (E-mail: director@amttf.in)