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Test code for machine tools —

Part 3: Determination of thermal effects

Code d'essai des machines-outils —

Partie 3: Évaluation des effets thermiques

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this part of ISO 230 may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

International Standard ISO 230-3 was prepared by Technical Committee ISO/TC 39, *Machine tools*, Subcommittee SC 2, *Test conditions for metal cutting machine tools*.

ISO 230 consists of the following parts, under the general title *Test code for machine tools*:

— *Part 1: Geometric accuracy of machines operating under no-load or finishing conditions*

— *Part 2: Determination of accuracy and repeatability of positioning numerically controlled axes*

— *Part 3: Determination of thermal effects*

— *Part 4: Circular tests for numerically controlled machine tools*

— *Part 5: Determination of the noise emission*

— *Part 6: Diagonal displacement test*

Annexes A to C of this part of ISO 230 are for information only.

Introduction

The purpose of ISO 230 is to standardize methods of testing the accuracy of machine tools, excluding portable power tools.

This part of ISO 230 specifies test procedures to determine thermal effects caused by a variety of heat inputs resulting in the distortions of a machine tool structure or the positioning system. It is a recognized fact that the ultimate thermo-elastic deformation of a machine tool is closely linked to the operating conditions. The test conditions described in this part of ISO 230 are not intended to simulate the normal operating conditions, but are to facilitate performance estimation and to determine the effects of environment on machine performance. For example, use of coolants may significantly affect the actual thermal behaviour of the machine. Therefore, these tests should be considered only as the preliminary tests towards the determination of actual thermo-elastic behaviour of the machine tool if such determination becomes necessary for machine characterization purposes. The tests are designed to measure the relative displacements between the component that holds the tool and the component that holds the workpiece as a result of thermal expansion or contraction of key structural elements.

The tests described in this part of ISO 230 can be used either for testing different types of machine tools (type testing) or testing individual machine tools for acceptance purposes. When the tests are required for acceptance purposes, it is up to the user to choose, in agreement with the supplier/manufacturer, those tests relating to the properties of the components of the machine which are of interest. The mere reference to this part of the test code for the acceptance tests, without agreement on the parts to be applied and the relevant charges, cannot be considered as binding for one or other of the contracting parties. One significant feature of this part of ISO 230 is its emphasis on environmental thermal effects on all the performance tests described in other parts of ISO 230 related to linear displacement measurements (such as linear displacement accuracy, repeatability and the circular tests). The suppliers/manufacturers should provide thermal specifications for the environment in which the machine can be expected to perform with the specified accuracy. The machine user should be responsible for providing a suitable test environment by meeting the supplier/manufacturer's thermal guidelines or otherwise accepting reduced performance. An example of environmental thermal guidelines is given in annex C.

A relaxation of accuracy expectations is required if the thermal environment causes excessive uncertainty or variation in the machine tool performance and does not meet supplier/manufacturer's thermal guidelines. If the machine does not meet the performance specifications, the analysis of the combined standard thermal uncertainty provides help identifying sources of problems. Combined standard thermal uncertainty is defined in 3.6 as well as in ISO 16015[1].

Test code for machine tools —

Part 3: Determination of thermal effects

1 Scope

This part of ISO 230 defines three tests, which are:

— environmental temperature variation error (ETVE) test;

— thermal distortion test caused by rotating spindles;

— thermal distortion test caused by moving linear axes.

The tests for thermal distortion caused by moving linear axes (see clause 7) are applicable to numerically controlled (NC) machines only and are designed to quantify the effects of thermal expansion and contraction of the axes on positioning accuracy and repeatability. For practical reasons, the test methods described in clause 7 apply to machines with linear axes up to 2 000 mm in length. If they are used for machines with axes longer than 2 000 mm, a representative length of 2 000 mm in the normal range of each axis should be chosen for the tests.

It should be noted that it is not foreseen to determine numerical tolerances for the tests described in this part of ISO 230.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of ISO 230. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of ISO 230 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 1:1975, *Standard reference temperature for industrial length measurements.*

ISO 230-1:1996, *Test code for machine tools — Part 1: Geometric accuracy of machines operating under no-load or finishing conditions.*

ISO 230-2:1997, *Test code for machine tools — Part 2: Determination of accuracy and repeatability of positioning numerically controlled axes.*

ISO 230-4:1996, *Test code for machine tools — Part 4: Circular tests for numerically controlled machine tools.*

3 Terms and definitions

For the purposes of this part of ISO 230, the following terms and definitions apply.

3.1
machine scale
measurement system integrated into a machine providing the linear or rotary position of the machine's axis

3.2
nominal differential thermal expansion
NDE
difference between the estimated expansion of a measured object and that of the test equipment owing to their temperatures deviating from 20 °C

3.3
uncertainty of nominal differential thermal expansion
u_{NDE}
combined uncertainty caused by the uncertainties of coefficients of thermal expansion of the measured object and that of the test equipment

NOTE It is obtained as the square root of the sum of the squares of the uncertainties of nominal expansions of the measured object and the test equipment.

3.4
environmental temperature variation error
ETVE[1)]
estimate of the maximum possible measurement uncertainty induced solely by the variation of the environment temperature during any time period while performance measurements are carried out on a machine tool

NOTE The notation $\mathrm{ETVE}_{(\mathrm{Z},\ 8\,°\mathrm{C})}$ indicates that the ETVE value is obtained along the Z direction and the value corresponds to an environmental temperature variation of 8 °C.

3.5
uncertainty due to environmental temperature variation error
u_{ETVE}

standard uncertainty in performance measurements caused by the effects of environmental temperature changes on the machine

NOTE 1 It is calculated as the square root of the square of ETVE divided by 12.

NOTE 2 The basis for the estimation of this uncertainty for a machine tool is the environment test according to clause 5.

3.6
combined standard thermal uncertainty[2)]
u_{CT}
combined uncertainty in length measurements caused by an environment with a temperature other than a constant and uniform 20 °C

NOTE 1 It is a combination by square root of sum of squares of uncertainty of environmental temperature variation error (u_{ETVE}), uncertainty of temperature measurements (u_{TM}) and the uncertainty of nominal differential thermal expansion (u_{NDE}).

NOTE 2 A detailed description of estimating the combined standard thermal uncertainty is given in ISO 16015[1].

3.7
$d_{\mathrm{X1},\ 60}$
range of displacement in the direction of the X axis observed at position P_1 (away from the spindle nose) within the first 60 min of the tests for thermal distortion caused by the rotating spindle

3.8
$d_{\mathrm{X1},\ t}$
range of displacement in the direction of the X axis observed at position P_1 (away from the spindle nose) within the total spindle running period, t, of the test for thermal distortion caused by the rotating spindle

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1) It is recognized that the ISO terminology requires the term “deviation” instead of the term “error” in this definition. However, due to the long history of ETVE usage, the committee agreed to keep the term as an exception to the above-mentioned ISO terminology.

2) This term is equivalent to “combined standard dimensional uncertainty due to thermal effects” defined in ISO 16015[1].

3.9
$d_{X2,\,60}$
range of displacement in the direction of the X axis observed at position P_2 (close to spindle nose) within the first 60 min of the test for thermal distortion caused by the rotating spindle

3.10
$d_{X2,\,t}$
range of displacement in the direction of the X axis observed at position P_2 (close to the spindle nose) within the total spindle running period, t, of the tests for thermal distortion caused by the rotating spindle

3.11
$d_{Y1,\,60}$
range of displacement in the direction of the Y axis observed at position P_1 (away from the spindle nose) within the first 60 min of the test for thermal distortion caused by the rotating spindle

3.12
$d_{Y1,\,t}$
range of displacement in the direction of the Y axis observed at position P_1 (away from the spindle nose) within the total spindle running period, t, of the test for thermal distortion caused by the rotating spindle

3.13
$d_{Y2,\,60}$
range of displacement in the direction of the Y axis observed at position P_2 (close to the spindle nose) within the first 60 min of the test for thermal distortion caused by the rotating spindle

3.14
$d_{Y2,\,t}$
range of displacement in the direction of the Y axis observed at position P_2 (close to the spindle nose) within the total spindle running period, t, of the tests for thermal distortion caused by the rotating spindle

3.15
$d_{Z,\,60}$
range of displacement in the direction of the Z axis within the first 60 min of the test for thermal distortion caused by the rotating spindle

3.16
$d_{Z,\,t}$
range of displacement in the direction of the Z axis within the total spindle running period, t, of the test for thermal distortion caused by the rotating spindle

3.17
$d_{A,\,60}$
range of angular deviation around the X axis within the first 60 min of the test for thermal distortion caused by the rotating spindle

3.18
$d_{A,\,t}$
range of angular deviation around the X axis within the total spindle running period, t, of the test for thermal distortion caused by the rotating spindle

3.19
$d_{B,\,60}$
range of angular deviation around the Y axis within the first 60 min of the test for thermal distortion caused by the rotating spindle

3.20
$d_{B,\,t}$
range of angular deviation around the Y axis within the total spindle running period, t, of the test for thermal distortion caused by the rotating spindle

3.21
$e1_{X,+}$
total range of thermal drift of the target position 1, in the direction of the X axis for the positive direction, during the test cycle

3.22
$e1_{X,-}$
total range of thermal drift of the target position 1, in the direction of the X axis for the negative direction, during the test cycle

3.23
$e2_{X,+}$
total range of thermal drift of the target position 2, in the direction of the X axis for the positive direction, during the test cycle

3.24
$e2_{X,-}$
total range of thermal drift of the target position 2, in the direction of the X axis for the negative direction, during the test cycle

3.25
$e1_{Y,+}$
total range of thermal drift of the target position 1, in the direction of the Y axis for the positive direction, during the test cycle

3.26
$e1_{Y,-}$
total range of thermal drift of the target position 1, in the direction of the Y axis for the negative direction, during the test cycle

3.27
$e2_{Y,+}$
total range of thermal drift of the target position 2, in the direction of the Y axis for the positive direction, during the test cycle

3.28
$e2_{Y,-}$
total range of thermal drift of the target position 2, in the direction of the Y axis for the negative direction, during the test cycle

3.29
$e1_{Z,+}$
total range of thermal drift of the target position 1, in the direction of the Z axis for the positive direction, during the test cycle

3.30
$e1_{Z,-}$
total range of thermal drift of the target position 1, in the direction of the Z axis for the negative direction, during the test cycle

3.31
$e2_{Z,+}$
total range of thermal drift of the target position 2, in the direction of the Z axis for the positive direction, during the test cycle

3.32
$e2_{Z,-}$
total range of thermal drift of the target position 2, in the direction of the Z axis for the negative direction, during the test cycle

4 Preliminary remarks

4.1 Measuring units

In this part of ISO 230, all linear dimensions and deviations are expressed in millimetres. All angular dimensions are expressed in degrees. Angular deviations are, in principle, expressed in ratios but in some cases, microradians or arcseconds may be used for classification purposes. The equivalent of the following expressions should always be kept in mind:

$$0{,}010/1\,000 = 10\ \mu\text{rad} \approx 2''$$

The temperatures are expressed in degrees Celsius (°C).

4.2 Reference to ISO 230-1

To apply this part of ISO 230, reference should be made to ISO 230-1, especially for the installation of the machine before testing and for the recommended accuracy of the testing equipment.

4.3 Recommended instrumentation and test equipment

The measuring instruments recommended here are only examples. Other instruments capable of measuring the same quantities and having the same or greater accuracy may be used. The following instrumentation and test equipment are recommended for clauses 5, 6 and 7:

a) displacement measuring system with adequate range, resolution, thermal stability, and accuracy (for example laser interferometer for thermal distortion caused by moving linear axes, capacitive, inductive or retractable contacting displacement sensors for environment testing and thermal distortion caused by rotating spindles);

b) temperature sensors (for example thermocouple, resistance or semiconductor thermometer) with sufficient resolution and accuracy;

c) data acquisition equipment, 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[3], and data is stored for subsequent analysis;

   NOTE Manual data processing is permissible if a computer system is not available.

d) test-mandrel, preferably made of steel with the design to be specified in machine-specific standards or agreed between supplier/manufacturer and user, see ISO 230-1:1996, clause A.3;

e) fixture in which to mount the displacement transducers, constructed preferably from steel with the design to be specified in machine-specific standards or agreed between supplier/manufacturer and user. The design should minimize local distortions caused by temperature gradients in the fixture.

When necessary and practicable, the axial displacement transducer (see Figures 1, 2 and 3) may be placed directly against the spindle nose to eliminate the effect of the thermal expansion of the test mandrel.

Long-term accuracy of the measuring equipment shall be verified, for example, by transducer drift tests (see clause A.5).

The measuring instruments shall be thermally stabilized before starting the tests.

3) Some temperature compensation systems exhibit cycle times shorter than 5 min. In such cases, the frequency for monitoring should be increased accordingly.

4.4 Machine conditions prior to testing

The machine shall be completely assembled and fully operational in accordance with the supplier's/manufacturer's instructions which must be recorded. All necessary levelling operations, geometric alignment and functional checks shall be completed satisfactorily before starting the tests.

The machine shall be powered up with auxiliary services operating and axes in “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, etc.

All tests shall be carried out with the machine in the unloaded condition. Where a machine involves rotating both the workpiece and the tool on separate spindles, the tests described in clauses 5 and 6 shall be carried out for each spindle with respect to a common fixed location on the machine structure. If any hardware or software based compensation capability or facilities for minimizing thermal effects, such as air or oil showers, are available on the machine tool they shall be used during the tests and the usage of these facilities shall be recorded.

4.5 Testing sequence

The tests described in clauses 5, 6 and 7 may be used either singly or in any combination. When used in combination, they should be executed in the same sequence as they are given in this part of ISO 230.

4.6 Test environment temperature

According to ISO 1, all dimensional measurements shall be made when the measuring instruments and the measured objects (for example machine tool) are in equilibrium with the environment where the temperature is kept at 20 °C. If the environment is at a temperature other than 20 °C, nominal differential thermal expansion (NDE) correction between the measurement system and the measured object (machine tool) has to be made to correct the results to correspond to 20 °C. For example, in a typical linear displacement measurement using laser interferometer, ambient temperature around the laser beam and the temperature of machine scale should be recorded during the measurements. The expected length change of the laser interferometer (due to change in laser wavelength as a function of the ambient temperature and pressure) and that of the machine scale (as a response to its temperature) shall be calculated. The difference between these two length expansions is calculated as NDE and used to correct the raw measurement data from the laser interferometer to determine the linear displacement deviations at 20 °C. However, in this part of ISO 230, since the aim is to identify the machine’s behaviour under possibly varying environmental temperature conditions, the requirement for NDE corrections is relaxed. NDE correction is allowed only between the test equipment and the part of the machine where the workpiece is usually located. Built in NDE correction used for the normal operation of machine tool shall be used; additional NDE correction just for the measurements shall not be used to correct the thermal distortions of machine scales.

5 Environmental temperature variation error (ETVE) test

5.1 General

Environmental temperature variation error (ETVE) tests are designed to reveal the effects of environmental temperature changes on the machine and to estimate the thermally induced error during other performance measurements. They shall not be used for machine comparison. ETVE shall be determined by the drift test using the procedure described in 5.2. If the correct operation of the measuring instrument requires compensation for environment factors such as air temperature and pressure, then these shall be used. If the measuring instrument incorporates facilities for NDE correction then these facilities should be used, provided that the material temperature sensor is placed on the part of the machine where the workpiece is normally located. The use of such facilities shall be recorded.

It is recommended that the supplier/manufacturer offer guidelines regarding the thermal environment which can be considered as acceptable for the machine to perform with the specified accuracy. Such general guidelines could contain, for example, a specification on the mean room temperature, maximum amplitude and frequency range of deviations from this mean temperature and environmental thermal gradients. It is the user's responsibility to provide an acceptable thermal environment for the operation and the performance testing of the machine tool at the installation site. However, if the user follows the guidelines provided by the machine supplier/manufacturer, the responsibility for machine performance according to the specifications reverts to the machine supplier/manufacturer.

The total uncertainty in the performance measurements of the machine tool caused by the thermal effects is defined as the combined standard thermal uncertainty. The combined standard thermal uncertainty (see 3.6) can be estimated with the help of the described test, when the environmental conditions during the performance measurement and the ETVE test are comparable. It shall not exceed an amount that is mutually agreed between the user and the supplier/manufacturer.

5.2 Test method

Figures 1, 2 and 3 show examples of typical measurement set-ups for a vertical- and horizontal-spindle machining centre and a turning centre, respectively. The fixture in which the displacement transducers are mounted shall be securely fixed to the non-rotating workholding or tool-holding zone of the machine to measure:

a) the relative displacements between the component that holds the tool and the component that holds the workpiece along the three orthogonal axes parallel to the axes of travel of the machine; the exact position of the measurement set-up shall be recorded along with the test results;

b) tilt or rotation around the X and Y axes of the machine tool.

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 and at the same elevation of the spindle nose should be monitored at least once every 5 min[4]. It is important to measure the ambient 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. Although the measured temperatures do not exactly correlate to the measured displacements, they are indications of the thermal changes in the environment and the machine structure.

NOTE To ensure the consistency of the ETVE results, it is necessary to monitor the ETVE testing process in such a way that significant changes in measurement conditions are recognizable.

Once set up, the drift test should be allowed to continue as long as possible, with a minimum deviation from normal performance measurement conditions. In situations where a periodic pattern of activity (such as periodic resetting of test equipment with respect to a measurement reference) is observed, the test duration should be over some period of time during which most events are repeated or any other duration agreed by the supplier/manufacturer and the user.

5.3 Interpretation of results

As a general rule, the results are plotted in graphs of thermal distortion and temperature versus time as shown in the example given in Figure 4. However, this resultant plot shall not be used for the purposes of machine comparison. The ETVE values obtained from such a plot are used for considering the combined standard thermal uncertainty in measurements such as linear displacement accuracy along each machine axis or the circular measurements in the three orthogonal planes of the machine work zone. In order to apply the combined standard thermal uncertainty to any performance measurement, the ambient temperature should be recorded continuously during that particular performance measurement process. If the recording shows a significant change of conditions compared to the conditions in which ETVE values were obtained, the ETVE results are null and void for that measurement process. In these cases, a re-evaluation of ETVE should be conducted, or conditions corrected to those for which the ETVE applies[5]. In addition, measuring instruments shall be thermally stabilized.

4) Some temperature compensation systems exhibit cycle times shorter than 5 min. In such cases, the frequency for monitoring should be increased accordingly.

5) Maximum variations of ambient temperature measured during machine performance tests should be smaller or equal to the change of ambient temperature measured during ETVE tests (clause 5).

