
**Test conditions for machining
centres —**

**Part 10:
Evaluation of thermal distortions**

Conditions d'essai des centres d'usinage —

Partie 10: Évaluation des déformations 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

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 39, *Machine tools*, Subcommittee SC 2, *Test conditions for metal cutting machine tools*.

This second edition cancels and replaces the first edition (ISO 10791-10:2007), which has been technically revised.

The main changes are as follows:

- thermal test T4 has been added;
- [Annex A](#) has been added.

A list of all parts in the ISO 10791 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

A machining centre is a numerically controlled machine tool capable of performing multiple machining operations, including milling, boring, drilling and tapping, as well as automatic tool changing from a magazine or similar storage unit in accordance with a machining programme. Most machining centres have facilities for automatically changing the direction in which the workpieces are presented to the tool.

The purpose of this document is to provide information on tests and checks which can be carried out for comparison, acceptance, maintenance or any other purpose.

[Annex A](#) presents three machining tests to evaluate thermal distortions of machining centres.

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Test conditions for machining centres —

Part 10: Evaluation of thermal distortions

1 Scope

This document specifies, tests for the evaluation of thermal distortions of the machine tool structure and positioning system, for machining centres with vertical spindle, with numerically controlled linear axes of lengths up to 5 000 mm for the X-axis and up to 2 000 mm for the Y- and Z-axis. It also applies to machining centres with horizontal spindle with numerically controlled linear axes of lengths up to 5 000 mm for the X-axis, 3 200 mm for the Y-axis and 2 000 mm for the Z-axis.

This document specifies four tests:

- environmental temperature variation error;
- thermal distortion caused by a rotating spindle;
- thermal distortion caused by moving linear axes;
- thermal distortion caused by rotary motion of components.

This document is intended to be used with ISO 230-3.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 230-1:2012, *Test code for machine tools — Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions*

ISO 230-3:2020, *Test code for machine tools — Part 3: Determination of thermal effects*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 230-1:2012 and ISO 230-3:2020 apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

4 Preliminary remarks

4.1 Measuring units

In this document, all linear dimensions and deviations are expressed in millimetres. All angular dimensions are expressed in degrees. Angular deviations are, in principle, expressed in ratios; however,

in some cases, microradians or arcseconds may be used for clarification 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 230-3

For the application of this document, reference shall be made to ISO 230-3:2020, 4.4 for the installation of the machine tool before testing, and shall be made to ISO 230-3:2020, Clauses 5, 6, 7 and 8 for the description of measuring methods and presentation of the results.

4.3 Measuring instruments

The measuring instruments recommended in this document are given only by way of examples. Other measuring instruments capable of measuring the same quantities and having the same or a smaller measurement uncertainty may be used. See ISO 230-3:2020, 4.3.

4.4 Testing sequence

The tests given in this document may be used either singularly or in any combination. Before each test, the machine tool should be in equilibrium with the environment. Therefore, a sufficient cooling down period between tests, generally at least as long as the thermal test, where parts of the machine tool have been heated, shall be planned and respected.

4.5 Tests to be performed

When testing a machine tool, it is not always necessary or even possible to carry out all the tests given in this document. When the tests are required for acceptance purposes, it is at the option of the user to choose, in agreement with the manufacturer/supplier, those tests relating to the components and/or the properties of the machine tool that are of interest. These tests are to be clearly stated when ordering a machine tool. Mere reference to this document for the acceptance tests, without specification of the tests to be carried out, and without agreement on the relevant expenses, cannot be considered as binding for any contracting party.

[Annex A](#) presents three machining tests to evaluate thermal distortions of machining centres, which can be performed as additional tests to the thermal tests in [Clause 5](#).

4.6 Diagrams

The diagrams shown in Tests T1 through T4 of this document illustrate only one test setup, for the reason of simplicity.

4.7 Tolerances

This document has no intention of assigning any numerical tolerances associated with the tests specified. Numerical tolerance for each parameter shall be agreed between manufacturer/supplier and user.

4.8 Software compensation

When software facilities are available for compensating some geometric errors, based on an agreement between the manufacturer/supplier and user, the relevant test can be carried out with these compensations. Some numerical thermal error compensations are based on temperature measurements on the machine tool structure, and others are based on operating conditions, e.g. the spindle rotation speed. Such a thermal compensation can be used, based on an agreement between the manufacturer/supplier and user. When any software compensation is used, this shall be stated in the test report.

5 Thermal tests

Object	T1					
Checking of environmental temperature variation error (ETVE)						
Diagram						
Key						
1 ambient air temperature sensor						
2 spindle bearing temperature sensor						
3 test mandrel						
4 linear displacement sensors						
5 fixture						
6 bolt for fixing the fixture						
l distance between measuring positions P1 and P2						
P1 measuring position 1						
P2 measuring position 2						
X1, X2, Y1, Y2, Z linear displacement sensors						
Tolerance						
Measured error						
Parameter	Time	$E_{TVE}(X)$	$E_{TVE}(Y)$	$E_{TVE}(Z)$	$E_{TVE}(A)$	$E_{TVE}(B)$
	min	mm	mm	mm	mm/mm	mm/mm
Measuring instruments						
temperature sensors, linear displacement sensors and test mandrel						

Observations and references to ISO 230-3:2020, 5.2 and 5.3

ETVE tests are designed to reveal the effects of environmental temperature changes on the machine tool with respect to deflection or deformation of the machine tool or its parts. They shall not be used for machine comparison.

The manufacturer/supplier should provide guidelines regarding the kind of thermal environment that should be acceptable for the machine tool to perform with the specified accuracy. It shall be the responsibility of the user to provide an acceptable thermal environment for the operation. However, if the user follows the guidelines provided by the machine tool manufacturer/supplier, the responsibility for machine tool performance according to the specification reverts to the machine tool manufacturer/supplier.

End surface of test mandrel needs proper flatness and squareness to axis of mandrel as these deviations influence measurement uncertainty directly.

Axes might warm-up when the machine axes are in "HOLD" (servo-on) mode, especially if they are in vertical direction. In such cases, the ETVE test should be carried out with all controls in "OFF". This shall be stated in the test report.

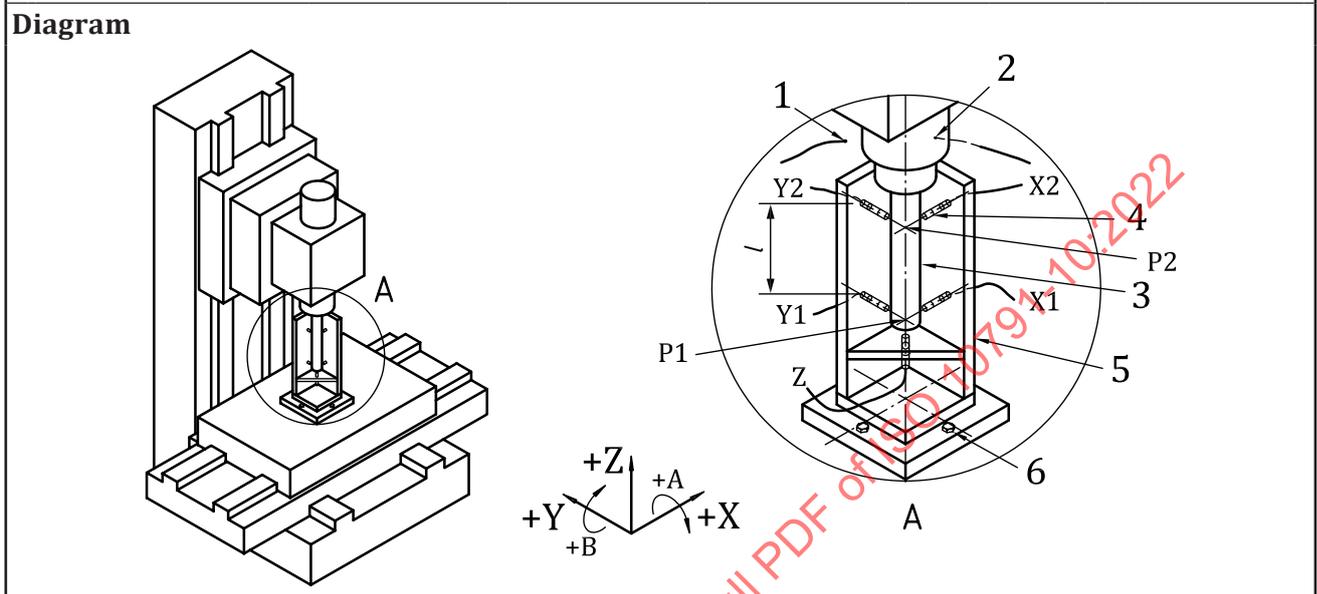
$E_{TVE}(Z)$ is the maximum range of thermal distortion in the Z direction over the test period of time. $E_{TVE}(Y)$ and $E_{TVE}(X)$ can be determined in the same way for the two other directions. For $E_{TVE}(A)$ and $E_{TVE}(B)$, see ISO 230-3:2020.

In addition to numerical values of the measured errors, a graphical presentation of results should be provided in accordance with ISO 230-3:2020, 5.4.

The following information shall be recorded:

- a) machine tool brand and model name;
- b) year of construction of machine tool, if available;
- c) machine tool serial number;
- d) time and date of test;
- e) location of the measurement setup;
- f) location of temperature sensors;
- g) type of sensors;
- h) design and material of the test mandrel and fixture;
- i) thermal compensation procedure;
- j) any special test procedures;
- k) machine preparation procedure prior to testing;
- l) power ON or OFF;
- m) positive direction of thermal distortion (if different from coordinate system).

Object T2
 Checking of thermal distortion caused by rotating spindles.
 One test per spindle shall be carried out.



- Key**
- 1 ambient air temperature sensor
 - 2 spindle bearing temperature sensor
 - 3 test mandrel
 - 4 linear displacement sensors
 - 5 fixture
 - 6 bolt for fixing the fixture
 - l* distance between measuring positions P1 and P2
 - P1 measuring position 1
 - P2 measuring position 2
 - X1, X2, Y1, Y2, Z linear displacement sensors

Tolerance

Measured error

	X1	Y1	Z	A	B
	mm	mm	mm	mm/mm	mm/mm
During first 60 min	$d(E_{X0(C)})_{P1,60}$ = ...	$d(E_{Y0(C)})_{P1,60}$ = ...	$d(E_{Z0(C)})_{60} = \dots$	$d(E_{A0(C)})_{60} = \dots$	$d(E_{B0(C)})_{60} = \dots$
After end of period <i>t</i> = ...	$d(E_{X0(C)})_{P1,t} = \dots$	$d(E_{Y0(C)})_{P1,t} = \dots$	$d(E_{Z0(C)})_t = \dots$	$d(E_{A0(C)})_t = \dots$	$d(E_{B0(C)})_t = \dots$
Distance, <i>l</i> = ...					

Measuring instruments
 temperature sensors, linear displacement sensors and test mandrel

Observations and references to ISO 230-3:2020, 6.2

User and manufacturer/supplier shall agree as to whether a constant spindle speed or a variable speed spectrum is used. For the case of constant spindle speed, they also shall agree on the spindle speed to be used. For the variable speed spectrum, they shall agree on the spindle speeds and time interval durations.

NOTE A possible speed spectrum cycle is a percentage of the maximum spindle speed for set period of time, followed by a spindle stop for another fixed period of time (e.g. maximum spindle speed followed by a stop). This cycle is then repeated for the complete test. The exact details of the speed spectrum can be discussed between the user and manufacturer/supplier.

The test shall last for 4 h plus 1 h with the spindle stopped.

In addition to numerical values of the measured errors, a graphical presentation of results should be provided in accordance with ISO 230-3:2020, 6.4.

The following information shall be recorded:

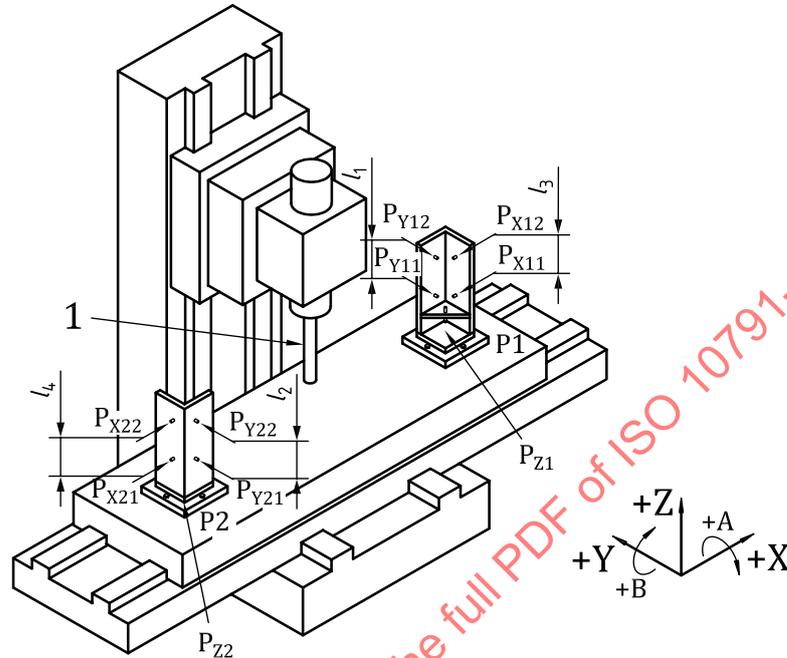
- a) machine tool brand and model name;
- b) year of construction of machine tool, if available;
- c) machine tool serial number;
- d) time and date of test;
- e) location of the measurement setup;
- f) location of temperature sensors;
- g) type of sensors;
- h) design and material of the test mandrel and fixture;
- i) thermal compensation procedure;
- j) any special test procedures;
- k) machine preparation procedure prior to testing;
- l) spindle speed regime, e.g. constant spindle speed or a variable speed spectrum (see ISO 230-3:2020, 6.2);
- m) positive direction of thermal distortion (if different from coordinate system);
- n) relative position of the spindle during measurement.

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Object T3

Checking of thermal distortion caused by the motion of linear axes

Diagram



Key

- 1 test mandrel
- l_1, l_2, l_3, l_4 distances between sensors used to calculate angular distortions
- $P_{X11}, P_{X12}, P_{Y11}, P_{Y12}$ linear displacement sensors at position P1
- P_{Z1}
- $P_{X21}, P_{X22}, P_{Y21}, P_{Y22}$ linear displacement sensors at position P2
- P_{Z2}

Tolerance

Measured error

	$d(E_{XX})_{P1}$	$d(E_{YX})_{P1}$	$d(E_{ZX})_{P1}$	$d(E_{XX})_{P2}$	$d(E_{YX})_{P2}$	$d(E_{ZX})_{P2}$
	mm	mm	mm	mm	mm	mm
Measured values at t=...						
Measured values at t=...						

	$d(E_{BX})_{P1}$	$d(E_{AX})_{P1}$	$d(E_{BX})_{P2}$	$d(E_{AX})_{P2}$
	mm/mm	mm/mm	mm/mm	mm/mm
Measured values at t=...				
Measured values at t=...				

Measuring instruments

temperature sensors, linear displacement sensors, and special test mandrel

Observations and references to ISO 230-3:2020, 7.2 and 7.2.2

In practice, there should be different feed speeds for principal and for auxiliary axes.

EXAMPLE A feed speed set for principal axes at 50 %, and one for auxiliary axes set at 20 % of the maximum feed speed.

The test cycle shall be made up of two time periods: 4 h of warming up the axis and 1 h for cooling it down. The measurements may be interrupted when the distortion change noted during the last 60 min is less than 15 % of the distortion registered over the initial 60 min of the test.

For each axis of the machine tool, the following plots versus time should be presented (for the example setup shown in Diagram above):

- two position plots of the target positions for the X-axis, one with $d(E_{XX})_{P1}$, $d(E_{YX})_{P1}$, $d(E_{ZX})_{P1}$, and the other with $d(E_{XX})_{P2}$, $d(E_{YX})_{P2}$, $d(E_{ZX})_{P2}$;
- two rotation plots of the target positions, for the X-axis pitch plots, one with $d(E_{BX})_{P1}$, and the other with $d(E_{BX})_{P2}$;
- two rotation plots of the target positions, for the X-axis roll plots, one with $d(E_{AX})_{P1}$, and the other with $d(E_{AX})_{P2}$;
- temperature plots of environment and machine tool during tests versus time.

See ISO 230-3:2020, 7.2.2 for the calculation of the position and rotation plots from the readings of the linear displacement sensors.

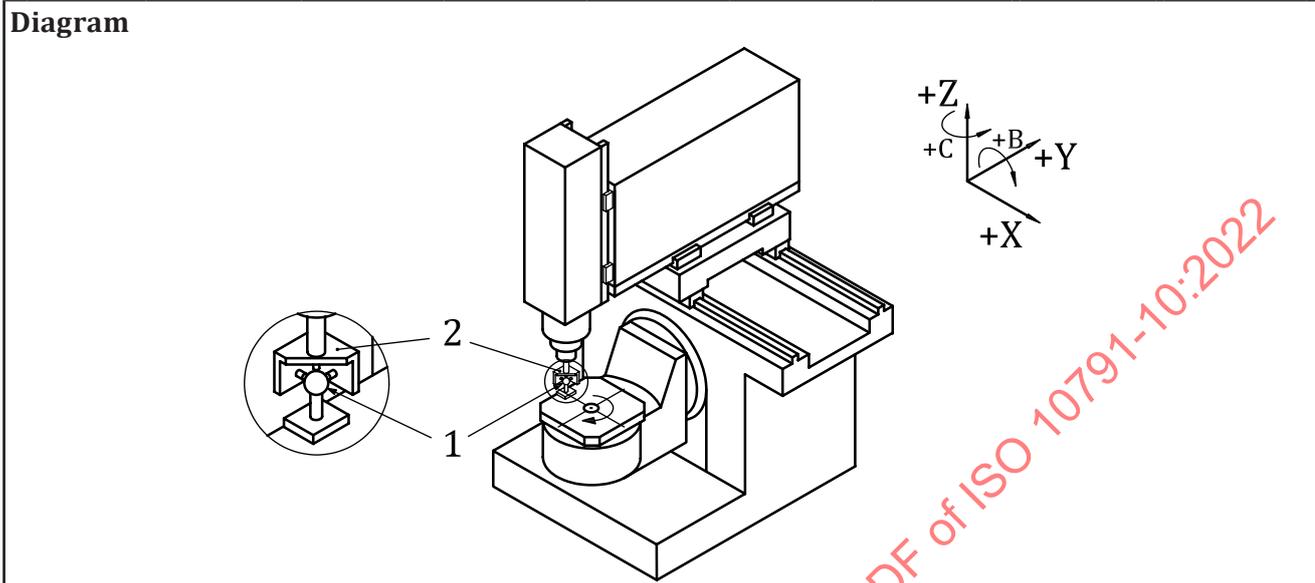
It should be noted that the results are influenced by the positioning repeatability of the machine tool axis under tests and the machine tool axes moved to take the measurements.

The following information shall be recorded:

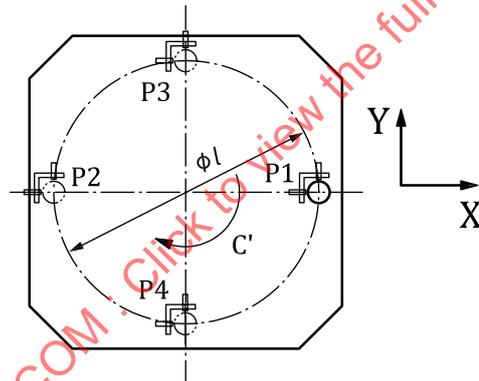
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- a) machine tool brand and model name;
- b) year of construction of machine tool, if available;
- c) machine tool serial number;
- d) time and date of test;
- e) location of measurement line;
- f) location of temperature sensor;
- g) feed speed;
- h) dwell times;
- i) start and end positions;
- j) compensation capabilities and facilities;
- k) instruments used;
- l) coefficient of thermal expansion used;
- m) warm-up procedures;
- n) temperature of the measured objects (for example, position transducer, slideway, bed, table, spindle head, and test mandrel. See ISO 230-3, 7.2.4);
- o) positive direction of thermal distortion in position and rotation (if different from coordinate system);
- p) design and material of the test mandrel and fixture;
- q) if relevant, conditions of any supply systems, e.g. lubrication, hydraulics, air supply, chillers.

Object T4
 Checking of thermal distortion due to the motion of rotary axis.



Four target positions P1 through P4 (only two sensors shown for the sensor nest):



- Key**
- 1 precision sphere
 - 2 special fixture with sensor nest
 - l* diameter of the nominal path of the target sphere centre
 - P1, P2, P3, P4 measurement target positions

NOTE An example setup for a rotary table with 360° rotation.

Tolerance

Measured error

	X	Y	Z	R	A	B	C
	mm	mm	mm	mm	mm/mm	mm/mm	mm/mm
Measured values at t=0	$d(E_{X0C})_t$	$d(E_{Y0C})_t$	$d(E_{Z0T})_t$	$d(E_{R0T})_t$	$d(E_{A0C})_t$	$d(E_{B0C})_t$	$d(E_{C0C})_t$
Measured values at t=...							

Diameter of the nominal path of the target sphere centre, $l = \dots$

Measuring instruments

special fixture with sensor nest, precision sphere and temperature sensors.

Observations and references to ISO 230-3:2020, 8.2

This test is carried out to identify the thermal distortion generated by the machine tool rotary positioning system observed between the workpiece and the tool. The test indicates the amount of the change in position and orientation of the rotary component at four angular positions, due to thermal influences on machine tool scales and deformations (twist and bend) of the machine tool structure caused by local generation of heat during the warm-up period.

For rotary heads and rotary tables with a range of rotation less than 360° , three (equally-spaced) target positions are selected, two of them near the end points of rotary motion. For those with a range of travel of 360° or more, four target positions 90° apart from each other are selected.

A precision sphere shall be mounted on the rotary component with a radial offset from the axis of rotation. A linear displacement sensor nest holding three sensors (aligned along the machine tool coordinate axes) shall be mounted at the opposite end of the structural loop to measure displacement between the tool and the workpiece side of the machine tool at the sphere centre. See Diagram above for an example of setup for rotary tables. Other setups providing similar information are also acceptable (see ISO 230-7:2015, Clause 6).

Similar test can be performed with the sphere positioned on the nominal axis of rotation. This setup eliminates the movement of linear axes, and thus the test results are not influenced by thermal influence on linear axis error motions. It also eliminates the influence of the angular positioning deviation of C-axis, E_{CC} . When the sphere is on the nominal axis of rotation, it can observe E_{X0C} , E_{Y0C} , and E_{Z0C} only.

The test cycle shall be made of two periods of time, 4 h of rotary axis cycling and 1 h cooling down. The measurements may be interrupted when the distortion change noted during the last 60 min is less than 15 % of the distortion registered over the first hour of the test. In situations where a set pattern of activity (for example periodic tool setting) is observed, the tests should be carried out over a period of time during which relevant events are repeated or over any other period of time agreed upon by the manufacturer/supplier and the user. Sufficient time should be allocated after each test to allow for the machine tool to cool-down.

Starting from one of the target positions, target position P1, where the machine tool will remain at rest long enough (dwell time) to record the readings of the displacement sensors, the rotary component shall be programmed to move to the target positions P2, and P3 (and P4 if applicable), where the corresponding set of displacement readings will be taken after moving the sensor nest to these positions via linear axes motion. The rotary component is then rotated continuously for a period of time after which displacement readings at target positions are taken. The period of continuous rotation is based on the agreement between the user and the manufacturer/supplier. This test sequence shall then be repeated until the end of the axis cycling period, recording data at the target positions. The programmed rotation speed and the dwell time at each target position is based on the agreement between the user and the manufacturer/supplier.

The exact procedure of the measurements should be reported.

At the end of the axis cycling period, the rotary component shall be stopped at the first target position; every 5 min it shall be moved to all other target positions to take readings, and then stopped again at the first position, until the end of the cool-down period.

Temperature measurements in some points of the machine tool can be helpful for the correct interpretation of the results. See ISO 230-3:2020 for example temperature sensor locations.

From the corresponding sensor readings at each target position, the change in position, orientation, and the radial and axial distortion of the rotary component are calculated. For a rotary axis along the C direction (see Diagram above), the following formulae can be used to calculate these distortions.

$$d(E_{X0C})_t = [(P_{x1} + P_{x2} + P_{x3} + P_{x4})/4]_t - [(P_{x1} + P_{x2} + P_{x3} + P_{x4})/4]_{t_0}$$

$$d(E_{Y0C})_t = [(P_{y1} + P_{y2} + P_{y3} + P_{y4})/4]_t - [(P_{y1} + P_{y2} + P_{y3} + P_{y4})/4]_{t_0}$$

$$d(E_{Z0T})_t = [(P_{z1} + P_{z2} + P_{z3} + P_{z4})/4]_t - [(P_{z1} + P_{z2} + P_{z3} + P_{z4})/4]_{t_0}$$

$$d(E_{R0T})_t = [(P_{x1} - P_{x2} + P_{y3} - P_{y4})/4]_t - [(P_{x1} - P_{x2} + P_{y3} - P_{y4})/4]_{t_0}$$

$$d(E_{A0C})_t = [(P_{z3} - P_{z4})_t - (P_{z3} - P_{z4})_{t_0}] / l \quad \text{or} \quad d(E_{A0C})_t = [(P_{z3} - (P_{z1} + P_{z2}) / 2)_t - (P_{z3} - (P_{z1} + P_{z2}) / 2)_{t_0}] / (l / 2)$$

$$d(E_{B0C})_t = - [(P_{z1} - P_{z2})_t - (P_{z1} - P_{z2})_{t_0}] / l \quad \text{or} \quad d(E_{B0C})_t = [(P_{z1} - (P_{z3} + P_{z4}) / 2)_t - (P_{z1} - (P_{z3} + P_{z4}) / 2)_{t_0}] / (l / 2)$$

$$d(E_{C0C})_t = [(P_{y1} - P_{y2} - P_{x3} + P_{x4})_t - (P_{y1} - P_{y2} - P_{x3} + P_{x4})_{t_0}] / (2 \cdot l)$$

where

l is the diameter of the nominal path of the target sphere centre

t_0 is the beginning of the test period

t is the end of the axis cycling period

P_{x1} is the reading of the displacement sensor in the direction of X-axis located at target position P1

It should be noted that the results are influenced by the positioning repeatability of the machine tool axis under test and the machine tool axes moved to take the measurements.

NOTE The formulae above are different from Formulae (55) to (62) in ISO 230-3:2020, 8.2. For example, ISO 230-3:2020, Formula (55) calculates $d(E_{X0C})_t$ by taking the measured X displacement at points P1 and P2 only. In the formulae above $d(E_{X0C})_t$ is calculated from all the points P1 to P4. The formulations can reduce the influence of e.g. measurement errors by an averaging effect.

For each rotary axis of the machine tool, plots of the three linear and angular distortions (X, Y, Z, A, B, C), and radial distortion versus time (corresponding to the machine X-, Y-, and Z-axes) should be presented.

In each of these plots the quantities of variations from the starting values as opposed to absolute values should be indicated.

In addition, the plots of the environment temperature and the machine temperatures measured during the test versus time should be provided.

The following parameters shall be reported along with the plots:

- a) rotational speed;
- b) dwell times;
- c) position of P1 with respect to the axis of rotation in the plane perpendicular to the axis of rotation;
- d) radial offset of the target sphere;
- e) axial offset of the target sphere (if applicable);
- f) compensation capabilities and facilities used;
- g) instrument and setup used;
- h) temperature sensor location;
- i) coefficient of thermal expansion used (if applicable);
- j) time and date of the test;
- k) warm-up procedures (including the time period of warm-up procedures);
- l) temperature of the measured object at the beginning and end of test;
- m) positive direction of position deviation;
- n) if relevant, conditions of any supply systems, e.g. lubrication, hydraulics, air supply, chillers

Annex A (informative)

Machining tests to evaluate thermal distortions

A.1 General

ISO 10791-7:2020 specifies machining tests under finishing conditions. By repeating the machining of a feature of the same geometry with constant time interval, and comparing the geometric error of the finished features, one can observe the change in the influence of the machine tool's error motions on the finished test pieces. This annex specifies such machining tests. The machine tool's thermal distortions, caused by internal and/or external heat sources, are typically a major contributor to the test result, although other factors can also affect it. The tests in [A.4](#) and [A.5](#) are for five-axis machining centres with two rotary axes, and the test in [A.3](#) is for all machining centres.

The test in [A.5](#) can be seen as an alternative to the test in [A.4](#). The test in [A.5](#) can have longer test times and both warm-up and cool-down phases (e.g. 4 h warm-up phase and 4 h cool-down phase). The measurement is easier for the test in [A.5](#); it can be measured by a handheld gauge.

The test in [A.5](#) is generally for a single rotary axis. If error separation between two rotary axes is necessary, then the test in [A.4](#) should be performed. The test in [A.5](#) evaluates the position of the finished faces in X, Y and Z directions, and the orientation around either X- or Y-axis, as well as the expansion of the test piece. The test in [A.4](#) evaluates the position and the orientation of two rotary axis average lines separately.

A.2 Reference to ISO 10791-7

For the application of this annex, reference shall be made to ISO 10791-7:2020, Clause 4, especially for the location of test pieces, the fixing of test pieces, material of test pieces, tooling, and cutting parameters, sizes of test pieces.

A.3 Machining test to evaluate the machine tool distortion in the axial direction of the tool

A.3.1 Test objective

The test objective is to check the relative displacement of the tool centre point to the test piece in the axial direction of the tool, when the heat is continuously generated by the spindle rotation.

If the thermal distortion during the environmental variation error test (EVE test) or during the test for thermal distortion caused by linear or rotary motion of components is approximately of the same amplitude as the test for thermal distortion caused by rotating spindles, then this test is a combined test of all these influences. In this case the relative displacement cannot be assigned to the spindle alone, e.g. for spindles that are thermally compensated.

A.3.2 Test procedure and the geometric definition of the test piece

[Figure A.1](#) shows the nominal geometry of the part blank. Four bolts or other clamping methods can be used to achieve enough stability and to minimize distortion.

For acceptance purposes, the manufacturer/supplier and user may agree on a certain warm-up cycle before the test, corresponding to particular requirements. If agreed, the test may be started without any warm-up cycle (cold start).

[Figure A.2](#) shows the nominal geometry of the finished test piece. This test is usually performed in the XY plane of the machine tool but can be performed in the other coordinate planes when an indexable spindle head is available.

A cylindrical end mill with diameter of 10 mm, or a corner radius end mill of the same diameter, should be used, but a different tool may be used based on an agreement between the manufacturer/supplier and user.

User and manufacturer/supplier shall agree as to whether a constant spindle speed or a variable speed spectrum is used for the warm-up cycle for 15 min. For the case of constant spindle speed, they also shall agree on the spindle speed to be used (e.g. 70 % of the maximum spindle speed). For the variable speed spectrum, they shall agree on the spindle speeds and time interval durations.

Cutting fluid applied should represent the typical application of the machine tool under test. If no typical application is defined for the machine tool under test, all the machining tests should be performed without cutting fluid (dry cut), or with the minimum quantity lubrication (MQL), although cutting fluid may be used based on an agreement between the manufacturer/supplier and user.

First, slot S1 is machined by slotting (with slot width equal to the tool diameter). The tool is fed only in the horizontal direction, i.e. no feed in the Z direction during machining operations. The axial depth of cut can be the same as the slot depth (minimum 1 mm) or it can be divided into multiple paths, based on an agreement between the manufacturer/supplier and user. Feed the tool to the inner pre-machined pocket.

Then, in the inner pocket, rotate the spindle in a constant speed or a variable speed spectrum for 15 min. Throughout the test, the tool shall not be moved in the Z direction to avoid the influence of the Z-axis linear positioning error.

The slot S2 is then machined by feeding the tool from the inner pocket to outside. Repeat the machining of each slot after every spindle rotation cycle for 15 min. The time when machining starts for each pocket shall be mentioned in the test report. The spindle should not stop throughout the entire test. A total of 16 slots, S1 to S16 in [Figure A.2](#), are machined (about 4 h).

The test piece geometry and test conditions may be modified based on an agreement between the manufacturer/supplier and user. The nominal depth of slots should be larger than the machine tool's expected maximum thermal distortion in the positive Z direction. The number of the slots to be machined may be reduced based on an agreement between the manufacturer/supplier and user.

Depending on the time it takes for thermal deformation to reach a steady state, the waiting time may be modified. If the change in the slot depth, as described in [A.3.3](#), does not change significantly after the first 5 slots, then the test may be repeated with the waiting time less than 15 min.

Temperature measurements in some points of the machine tool can be helpful for the correct interpretation of the results. See ISO 230-3:2020, 6.2 for example temperature sensor locations. The temperature of the test piece over the entire test should be periodically measured and reported.

The orientation of the test piece should be marked on the top surface for the recognition of its orientation in the measurement.

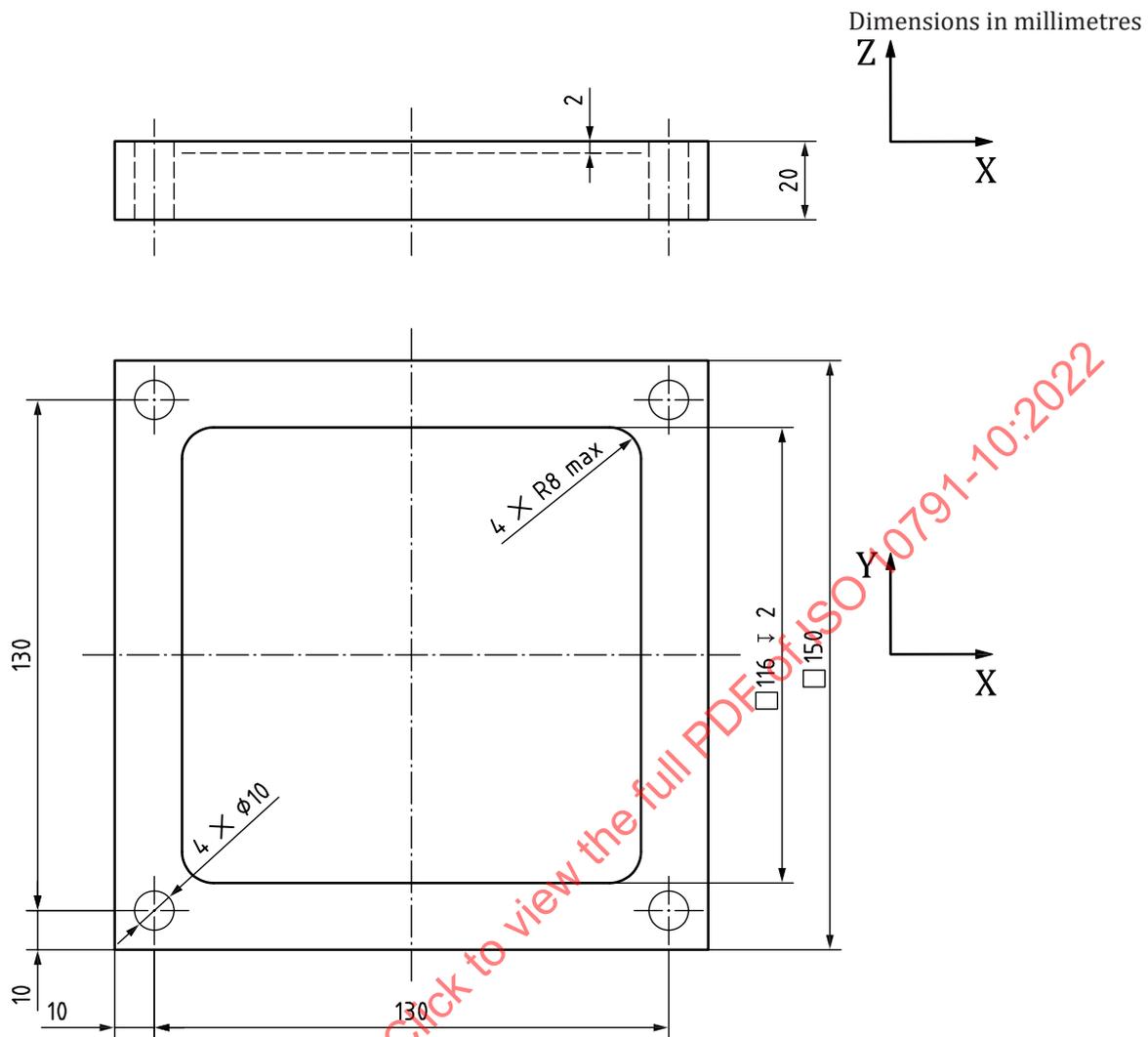


Figure A.1 — Part blank for the test piece

- repeatability of probing (expressed as maximum range of Z values of all slots),
- surface finish of the machined surfaces,
- thermal distortion of the test piece,
- thermal influence on the machine tool's positioning during the measurement.

A.3.5 Test report

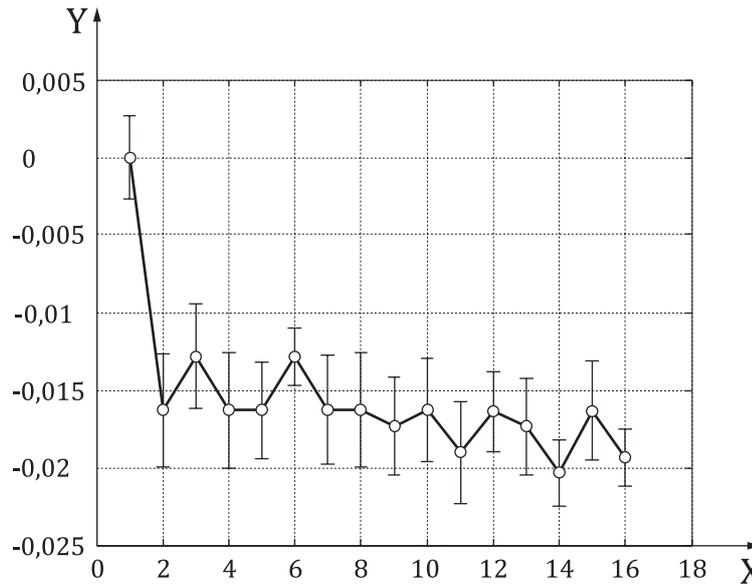
The example test report is depicted in [Table A.1](#).

The measured slot depth differences from the first slot versus the slot number, or the time of machining, should be graphically represented. [Figure A.3](#) shows an example.

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Table A.1 — Example test report

Cutting conditions	<ul style="list-style-type: none"> — Machining centre: — Test date: — Test piece: <ul style="list-style-type: none"> — Material: — Nominal dimensions of slots: — Warm-up cycle: — Spindle speed: — Cutting tool: <ul style="list-style-type: none"> — Diameter: — Length: — Number of teeth: — Material, coating: <ul style="list-style-type: none"> — Corner radius of tool: — Cutting parameters: — Feed speed: 																																								
Measured values	<p>Measuring instrument:</p> <table border="1" data-bbox="419 1126 1460 1538"> <thead> <tr> <th>Slot number</th> <th>Starting time of machining [min: s]</th> <th>Average of the measured differences in the depth from the first slot [mm]</th> <th>Range of measured Z values [mm]</th> <th>Test piece temperature [°C]</th> </tr> </thead> <tbody> <tr> <td>S1</td> <td>0</td> <td>--</td> <td></td> <td></td> </tr> <tr> <td>S2</td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td>S3</td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td>...</td> <td>...</td> <td>...</td> <td></td> <td></td> </tr> <tr> <td>...</td> <td>...</td> <td>...</td> <td></td> <td></td> </tr> <tr> <td>S15</td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td>S16</td> <td></td> <td></td> <td></td> <td></td> </tr> </tbody> </table>	Slot number	Starting time of machining [min: s]	Average of the measured differences in the depth from the first slot [mm]	Range of measured Z values [mm]	Test piece temperature [°C]	S1	0	--			S2					S3							S15					S16				
Slot number	Starting time of machining [min: s]	Average of the measured differences in the depth from the first slot [mm]	Range of measured Z values [mm]	Test piece temperature [°C]																																					
S1	0	--																																							
S2																																									
S3																																									
...																																							
...																																							
S15																																									
S16																																									



Key

- X index number of slots
- Y slot depth mm

NOTE The error bars represent the range of measured Z values at each slot.

Figure A.3 — Example graphical presentation of test results

A.4 Machining test to evaluate the thermal distortion of five-axis machining centres

A.4.1 Test objective

This test is applicable to all five-axis machining centres with three linear and two rotary axes. The test objective is to check the change in the accuracy of angular positioning and of the position and the orientation of rotary axis average lines, under thermal influence. The test is an extension of the M4 test in ISO 10791-7:2020, Clause 5.

A.4.2 Premachining

Figure A.4 shows the nominal geometry of the part blank. The depth of cut in the finishing shall be nominally constant both in axial and radial directions. The radial and axial depths of cut in the finishing shall be agreed between the manufacturer/supplier and user. Figure A.4 shows an example only, with the finishing allowance of 0,1 mm.

The test piece should be premachined by feeding linear axes only (at, e.g. $B' = C' = 0^\circ$ for the machine configuration shown in Figure A.6).

The workpiece coordinate system for the finishing (see Figure A.5) should be defined with its origin at the Z position 0,1 mm below the bottom face of the first step on the part blank, so that the finishing path is subject to the axial depth of cut of 0,1 mm at $B' = 0^\circ$.

The finishing should be conducted without unclamping the premachined part blank.

A.4.3 Geometric definition of the test piece

Figure A.5 shows the nominal geometry of the finished test piece.

The nominal geometry shown in [Figure A.5](#) is an example only. It may be modified based on an agreement between the manufacturer/supplier and user. The number of steps (total 12, or four sets, as a default) may be increased based on the agreement between the manufacturer/supplier and user, which can facilitate the observation of the velocity of thermal changes, or the approach to a thermal steady state.

Depending on the test piece's size or shape, it can show faster reaction to environmental changes, e.g. thermal change due to opening or closing of the machine door. The influence can result in different test results when the test piece is much larger than [Figure A.5](#).

Thermal influence on the finished test piece geometry can be significantly dependent on the machine configuration. The number of the steps and the warm-up time interval (15 min by default) may be modified depending on the machine configuration.

In [Figure A.5](#),

$S_{n,m,*}$ represents the name of each machined face,

where

- $n = 1, \dots, 12$: step number (topmost: 1)
- $m = 1, \dots, 4$: 1 for -Y side face, 2 for +X side face, 3 for +Y side face, and 4 for -X side face.
- *: s for side face, b for bottom face.

For machine tools with a rotary axis on the workpiece side, the part blank should be placed concentric to the axis of the rotary table.

The orientation of the test piece should be marked on the top surface for the recognition of its orientation in the measurement.

Dimensions in millimetres

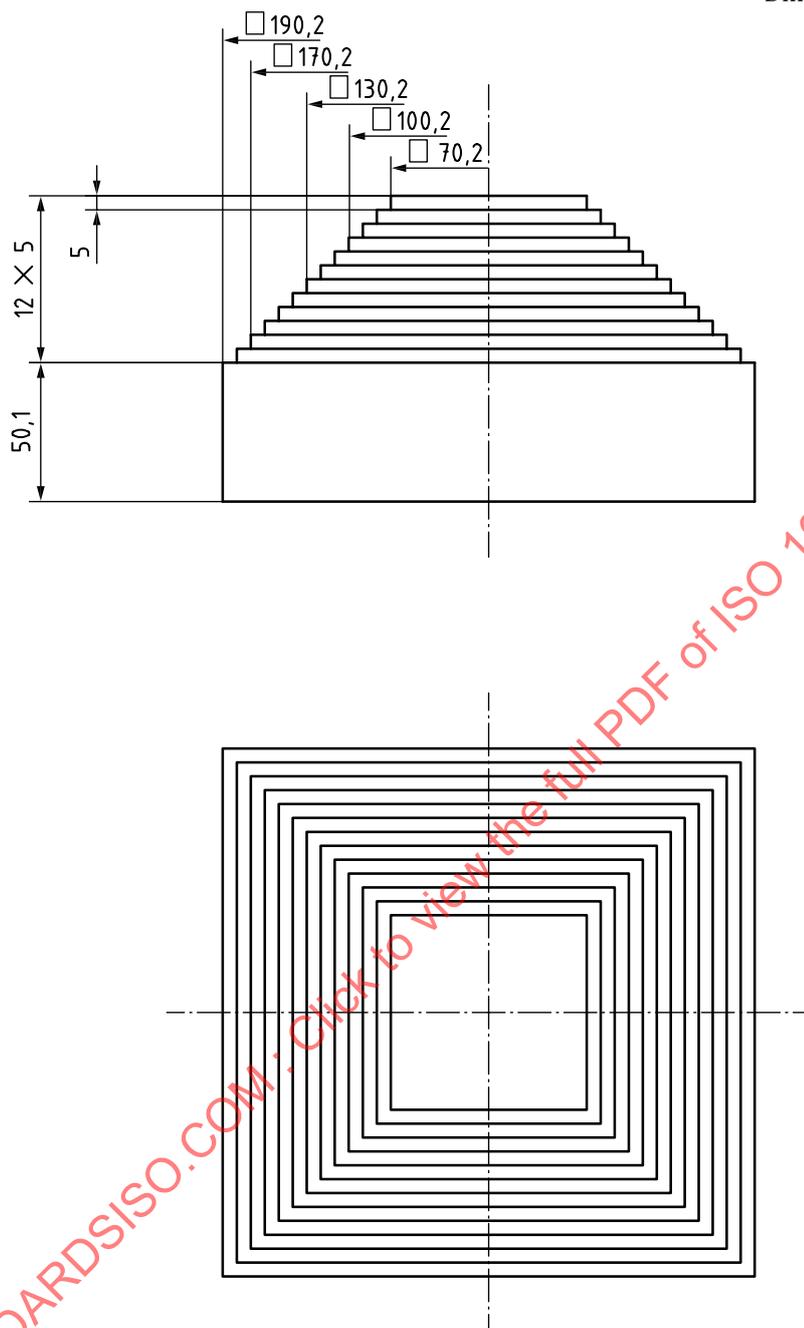


Figure A.4 — The shape and dimensions of the part blank, leaving a finishing allowance

Dimensions in millimetres

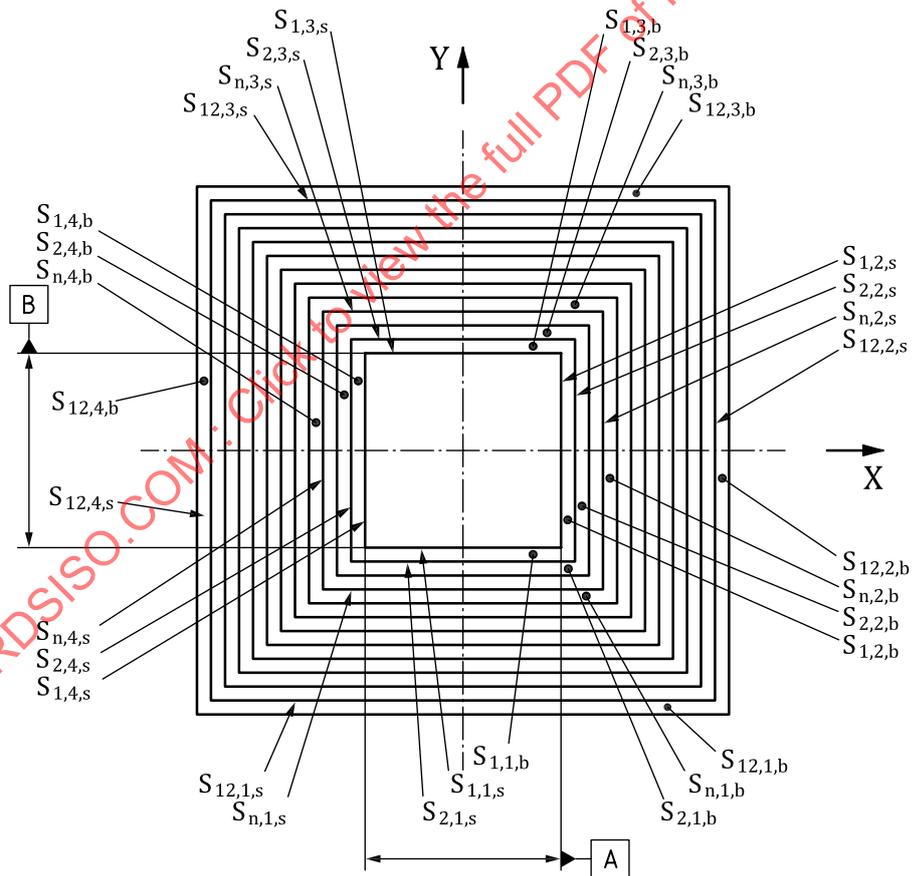
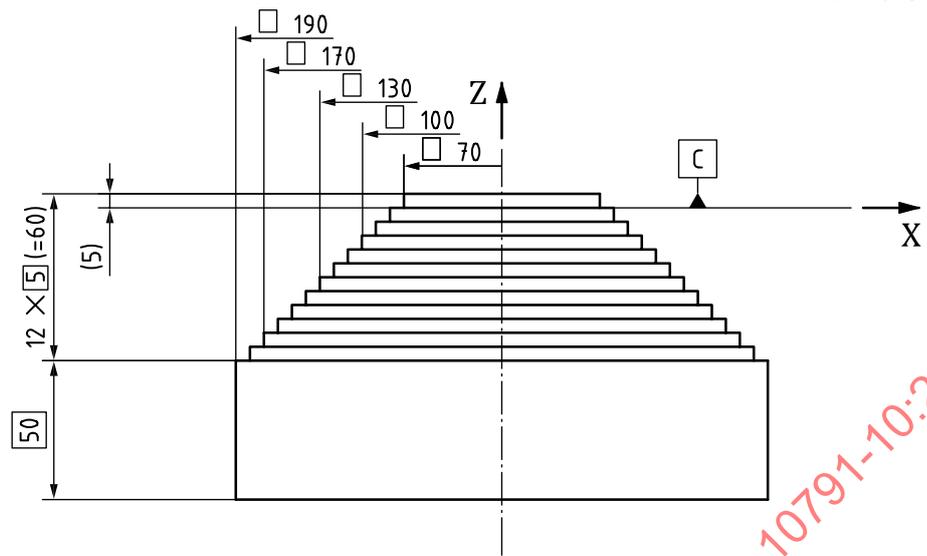


Figure A.5 — Finished test piece geometry

A.4.4 Test procedure

A.4.4.1 General

The manufacturer/supplier and user may agree on a certain warm-up cycle before the test, corresponding to particular requirements. If agreed, the test may be started without any warm-up cycle (cold start).

A cylindrical end mill with diameter of 10 mm, or a corner radius end mill of the same diameter, should be used, but a different tool may be used based on an agreement between the manufacturer/supplier and user.

Cutting fluid applied should represent the typical application of the machine tool being tested. If no typical application is defined for the machine tool being tested, all the machining tests should be performed without cutting fluid (dry cut), or with the minimum quantity lubrication (MQL), although cutting fluid may be used based on an agreement between the manufacturer/supplier and user.

First, a set of first three steps, $S_{1,m,*}$ to $S_{3,m,*}$ ($m = 1, \dots, 4$ and $* = s/b$), are machined as described in [A.4.4.2](#) (for machine tools with two rotary axes in the workpiece side) or [A.4.4.3](#) (for machine tools with two rotary axes in the tool side). This set of three steps is called the first set.

Then, at the retracted Z position, perform the warm-up cycle for 15 min. The warm-up cycle shall be agreed between the manufacturer/supplier and user. For example, rotate the spindle in a constant speed or a variable speed spectrum for 15 min. For the case of constant spindle speed, they also shall agree on the spindle speed to be used (e.g. 70 % of the maximum spindle speed). For the variable speed spectrum, they shall agree on the spindle speeds and time interval durations. It can be by the reciprocal motion of a linear axis (axes) or a rotary axis, or the environmental temperature variation error (ETVE).

Then, repeat the “Machining sequence” below for the next set of three steps, $S_{4,m,*}$ to $S_{6,m,*}$ ($m = 1, \dots, 4$ and $* = s/b$). The time when machining is finished for each set should be reported. This is repeated until total four sets (12 steps) are machined.

All the faces should be finished by repeating the same finishing path twice (i.e. zero nominal depth of cut). Cutting parameters are subject to agreement between manufacturer/supplier and user of the machine tool.

A.4.4.2 Machining sequence (for machine tools with two rotary axes in the workpiece side)

The following shows the machining sequence for a five-axis machining centre with a rotary table (C'-axis) on a swivelling axis (B'-axis) (see [Figure A.6](#)). For different axis configurations (e.g. C'-axis on A'-axis), a similar procedure shall be applied.

a) **Step 1:** The first square step, consisting of the faces $S_{1,m,*}$ ($m = 1, \dots, 4$ and $* = s/b$), is machined by end milling using two linear motions (X- and Y-axes). See [Figure A.7 a](#)).

The cutting direction may be agreed between the manufacturer/supplier and user. It shall be the same throughout Steps 1 to 3. The cutting direction shown in [Figure A.7](#) (up-cut) is an example only.

b) **Step 2:** The second square step is machined by end milling with the following machining sequence:

- At $B' = 0^\circ$ and $C' = 0^\circ$, finish the face, $S_{2,1,s/b}$, by feeding toward the X direction, and then finish the face, $S_{2,2,s/b}$, by feeding toward the Y direction. See [Figure A.7 b](#)).
- Rotate the test piece with the C'-axis by 180° . Finish the faces, $S_{2,3,s/b}$ and $S_{2,4,s/b}$, similarly by feeding toward the X- and then the Y direction. See [Figure A.7 c](#)).

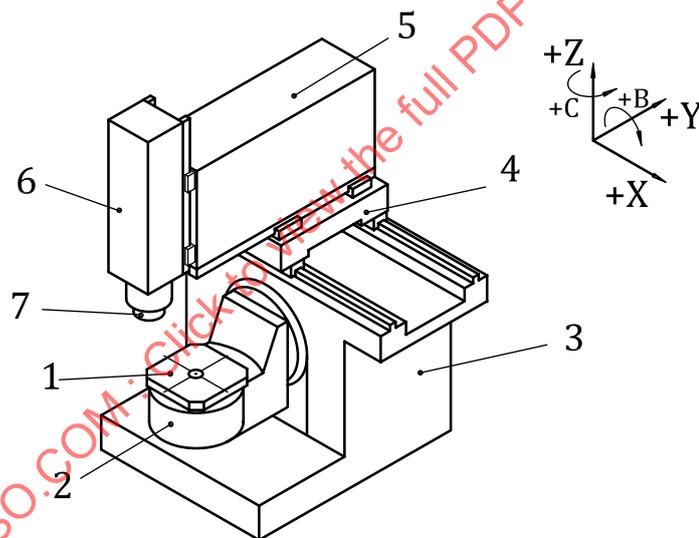
c) **Step 3 for a swivelling axis (B'-axis) that can be indexed at $\pm 90^\circ$,** the third square is machined as follows:

- The faces, $S_{3,4,s/b}$, are finished at $B' = -90^\circ$ and $C' = 0^\circ$ by feeding toward the Y direction. See [Figure A.7 d](#)).

- The faces, $S_{3,2,s/b}$, are finished at $B' = -90^\circ$ and $C' = 180^\circ$ by feeding toward the Y direction. See [Figure A.7 d](#)).
- The faces, $S_{3,1,s/b}$, are finished at $B' = +90^\circ$ and $C' = 270^\circ$ by feeding toward the Y direction. See [Figure A.7 e](#)).
- The faces, $S_{3,3,s/b}$, are finished at $B' = +90^\circ$ and $C' = 90^\circ$ by feeding toward the Y direction. See [Figure A.7 e](#)).

d) **Step 3 for a swivelling axis that cannot be indexed at $\pm 90^\circ$ (only at -90°)**, the third square is machined as follows:

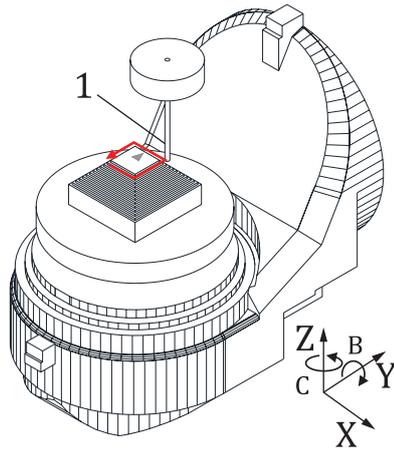
- The faces, $S_{3,4,s/b}$, are finished at $B' = -90^\circ$ and $C' = 0^\circ$ by feeding toward the Y direction. See [Figure A.7 d](#)).
- The faces, $S_{3,2,s/b}$, are finished at $B' = -90^\circ$ and $C' = 180^\circ$ by feeding toward the Y direction. See [Figure A.7 d](#)).
- The faces, $S_{3,1,s/b}$, are finished at $B' = -90^\circ$ and $C' = 90^\circ$ by feeding toward the Y direction. See [Figure A.7 d](#)).
- The faces, $S_{3,3,s/b}$, are finished at $B' = -90^\circ$ and $C' = 270^\circ$ by feeding toward the Y direction. See [Figure A.7 d](#)).



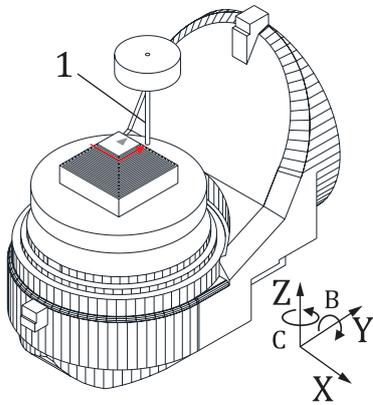
Key

- | | |
|----------------------------|-------------------------|
| 1 rotary table (C'-axis) | 5 column (Y-axis) |
| 2 tilting cradle (B'-axis) | 6 spindle head (Z-axis) |
| 3 bed | 7 spindle [(C1)-axis] |
| 4 column saddle (X-axis) | |

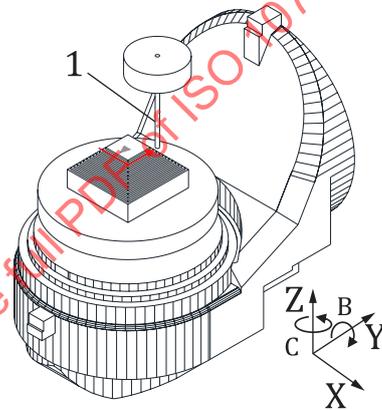
Figure A.6 — Example of a vertical five-axis machining centre with a tilting rotary table [w C' B' b X Y Z (C1) t]



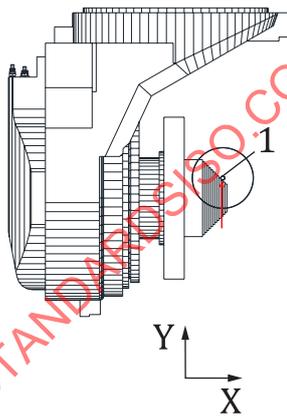
a) Machining of $S_{1,1,s/b}$, $S_{1,2,s/b}$, $S_{1,3,s/b}$, and $S_{1,4,s/b}$ at $B' = 0^\circ$ and $C' = 0^\circ$



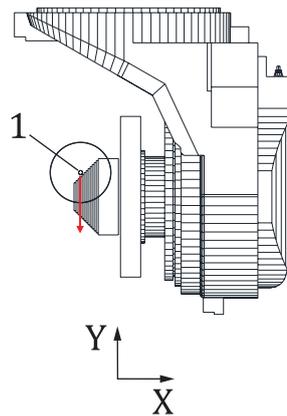
b) Machining of $S_{2,1,s/b}$ and $S_{2,2,s/b}$ at $B' = 0^\circ$ and $C' = 0^\circ$



c) Machining of $S_{2,3,s/b}$ and $S_{2,4,s/b}$ at $B' = 0^\circ$ and $C' = 180^\circ$



d) Machining of $S_{3,4,s/b}$ at $B' = -90^\circ$ and $C' = 0^\circ$



e) Machining of $S_{3,1,s/b}$ at $B' = 90^\circ$ and $C' = 270^\circ$

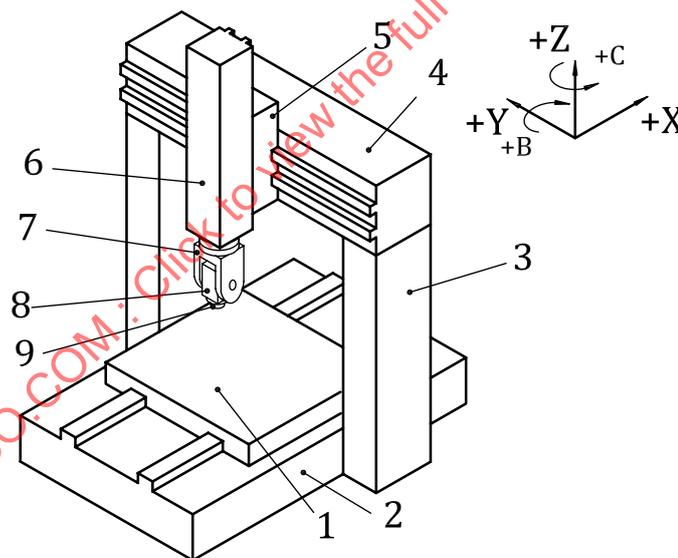
Key
1 tool

Figure A.7 — Machining procedure for machine tools with two rotary axes in the workpiece side

A.4.4.3 Machining sequence (for machine tools with two rotary axes in the tool side):

The following shows the machining sequence for a five-axis machining centre with a tilting head (B-axis) mounted on a swivelling head (C-axis) (See [Figure A.8](#)). For different axis configurations (e.g. A-axis on C-axis), similar procedure shall be applied.

- a) **Step 1:** The first square step, consisting of the faces $S_{1,m,*}$ ($m = 1, \dots, 4$ and $* = s/b$), is machined by end milling using two linear motions (X- and Y-axes).
- b) **Step 2:** The second square is machined as follows:
 - At $B = 0^\circ$ and $C = 0^\circ$, finish the faces, $S_{2,1,s/b}$, by end milling toward the X direction, and then finish the faces, $S_{2,2,s/b}$, by feeding toward the Y direction.
 - Rotate the C-axis by 180° . Finish the faces, $S_{2,3,s/b}$, toward the X direction, and then finish the faces, $S_{2,4,s/b}$, by feeding toward the Y direction.
- c) **Step 3:** the third square is machined as follows:
 - The faces, $S_{3,2,s/b}$, are finished at $B = +90^\circ$ and $C = 0^\circ$ by feeding toward the Y direction.
 - The faces, $S_{3,4,s/b}$, are finished at $B = -90^\circ$ and $C = 0^\circ$ by feeding toward the Y direction.
 - The faces, $S_{3,1,s/b}$, are finished at $B = +90^\circ$ and $C = 270^\circ$ by feeding toward the X direction.
 - The faces, $S_{3,3,s/b}$, are finished at $B = -90^\circ$ and $C = 270^\circ$ by feeding toward the X direction.



Key

1	table (X'-axis)	6	ram (Z-axis)
2	bed	7	swivelling head (C-axis)
3	column	8	tilting head (B-axis)
4	cross beam	9	spindle [(C1)-axis]
5	ram saddle (Y-axis)		

Figure A.8 — Example of a vertical five-axis machining centre with two rotary axes in the spindle head [w X' b Y Z C B (C1) t]

A.4.5 Measurement

See [Table A.2](#). All the features should be measured by using a coordinate measuring machine (CMM).

Alternatively, on-machine measurement using a probe, e.g. a touch-trigger probe, on the same machine tool, is possible. All the points shall be measured at the same angular positions of the two rotary axes, e.g. $B = C = 0^\circ$ for the machine configuration shown in [Figure A.6](#). It eliminates the influence of rotary axis geometric errors, although linear axis error motions can be major measurement uncertainty contributors. On-machine measurement shall be done in a thermally stable condition.

Four or more points on each face should be probed. [Figure A.9](#) shows recommended positions of probed points (on the finished surfaces $S_{1,2,s}$ and $S_{1,2,b}$ as an example):

- Height of probing on side face: 3 mm
- Distance from edge for side and bottom face: 5 mm
- Distance between points: 20 mm

All the finished faces shall be probed in the same manner.

The measurement coordinate system is defined as follows:

- Probe 16 points on the datum plane C (see [Figure A.5](#)) to define the direction of Z-axis.
- Probe 8 points on each of the faces $S_{1,1,s}$ and $S_{1,3,s}$ to define the planes, and take their intersection lines with the datum plane C, or, probe 4 points on the line parallel to the datum plane C on each of $S_{1,1,s}$ and $S_{1,3,s}$ and take their projected lines onto the datum plane C. The datum plane B contains their symmetry line and is perpendicular to the datum plane C. The X-axis is parallel to the datum plane B.
- Similarly define the datum plane A from the probed points $S_{1,2,s}$ and $S_{1,4,s}$. The origin of measurement coordinate system is defined at the intersection of the datum planes A, B and C.

In [Table A.2](#), the position error of one surface to the other surface is defined as follows. The position error in Y of $S_{n,3,s}$ to $S_{n,1,s}$ ($n = 2, 5, 8, 11$) (#7 in [Table A.2](#)) is taken as an example (see [Figure A.10 a](#)):

- Calculate the reference straight line of the probed points on $S_{n,3,s}$ by e.g. the least square fit (see ISO 230-1:2012, 3.4.14). For other options, see ISO 230-1:2012, 3.4.12.
- Take the intersection of this reference straight line and the YZ plane of the measurement coordinate system.
- Similarly, take the intersection of this reference straight line of the probed points on $S_{n,1,s}$ and the YZ plane of the measurement coordinate system.
- The position error in Y of $S_{n,3,s}$ to $S_{n,1,s}$ is the distance of these two points projected onto the XY plane of the measurement coordinate system minus the nominal distance between $S_{n,3,s}$ and $S_{n,1,s}$.

Similarly, the parallelism error in the ZX plane (rotation B) of $S_{n,1,b}$ to $S_{1,1,b}$ ($n = 1, 4, 7, 10$) (#5 in [Table A.2](#) as an example of angular errors) is calculated as follows (see [Figure A.10 b](#)):

- Calculate the reference straight line for the probed points on $S_{n,3,b}$, and that for $S_{1,1,b}$.
- The angle between the two reference straight lines projected onto the ZX plane is the parallelism error in the ZX plane (rotation B) of $S_{n,1,b}$ to $S_{1,1,b}$. The parallelism error is expressed in the displacement over 70 mm (the shortest part length).

Dimensions in millimetres

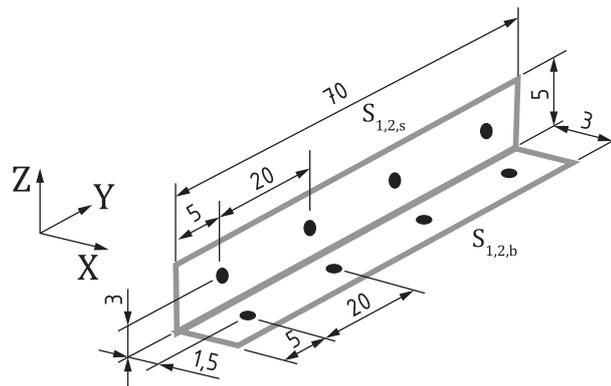
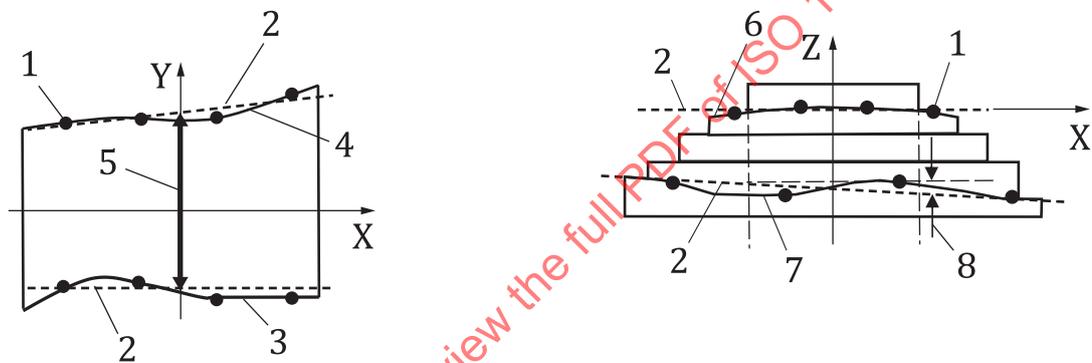


Figure A.9 — Recommended positions of probed points (on the finished surfaces $S_{1,2,s}$ and $S_{1,2,b}$ as an example)



a) Position error in Y-direction of $S_{n,3,s}$ to $S_{n,1,s}$

b) Parallelism error in ZX plane of $S_{n,1,b}$ to $S_{1,1,b}$

Key

- | | | | |
|---|------------------------------|---|---|
| 1 | probed point | 5 | position error in Y of $S_{n,3,s}$ to $S_{n,1,s}$ |
| 2 | reference straight line | 6 | machined surface, $S_{1,1,b}$ |
| 3 | machined surface $S_{n,1,s}$ | 7 | machined surface $S_{n,1,b}$ |
| 4 | machined surface $S_{n,3,s}$ | 8 | parallelism error in ZX plane of $S_{n,1,b}$ to $S_{1,1,b}$ (for 70 mm) |

Figure A.10 — Calculation of a) the position error in Y of $S_{n,3,s}$ to $S_{n,1,s}$ and b) the parallelism error in ZX plane of $S_{n,1,b}$ to $S_{1,1,b}$

A.4.6 Measurement uncertainty contributors

Factors that can influence the uncertainty of the measurement include:

For the measurement on the same machine tool:

- uncertainty of the measuring instrument,
- accuracy of positioning of machine tool axes by linear axes,
- surface finish of the machined surfaces,
- thermal distortion of the test piece,
- thermal influence on the machine tool's positioning during the measurement.

For the measurement on a CMM:

- measurement uncertainty of the CMM,
- surface finish of the machined surfaces,
- thermal distortion of the test piece,
- distortion of the test piece due to unclamping.

A.4.7 Test report

An example test report is depicted in [Table A.2](#).

The change in each measured value should be graphically represented. [Figure A.11](#) shows an example.

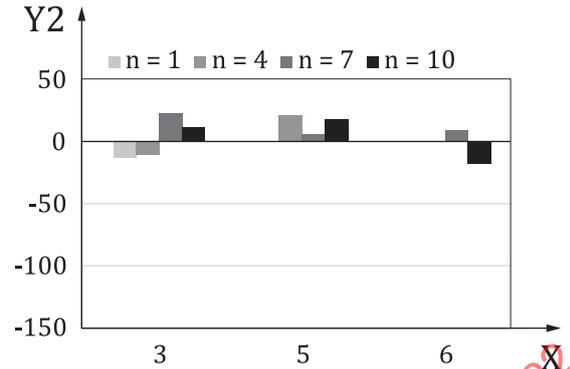
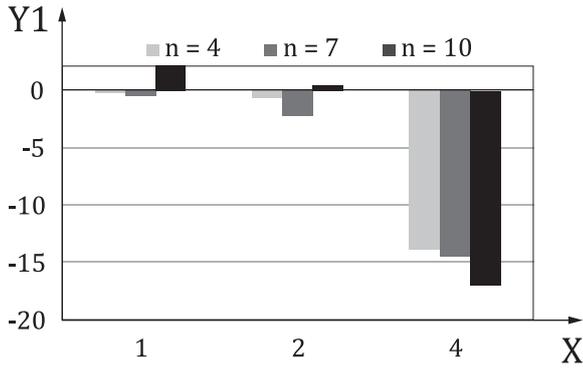
NOTE 1 The geometric errors of the first set (the steps $n = 1, 2, 3$) of the finished test piece show the influence of the machine tool's volumetric errors, including the influence of position and orientation errors of rotary axis average lines, when the machine tool is at thermally initial condition. Their change for each set shows the thermal influence on the machine tool's volumetric errors.

NOTE 2 The rightmost column of [Table A.2](#) shows major error causes for each evaluation item. It only shows position and orientation errors of rotary axis average lines as major error causes. Other error motions can also contribute. For example, error motions of linear axes can be potentially critical error contributors.

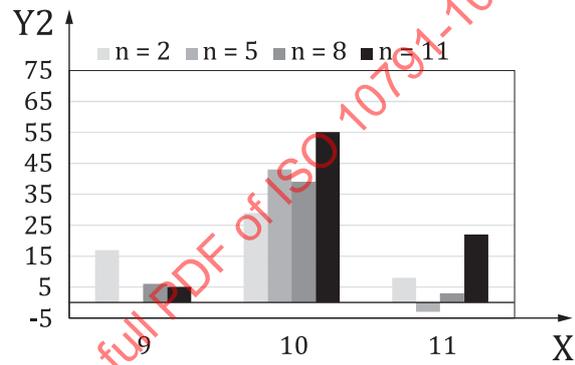
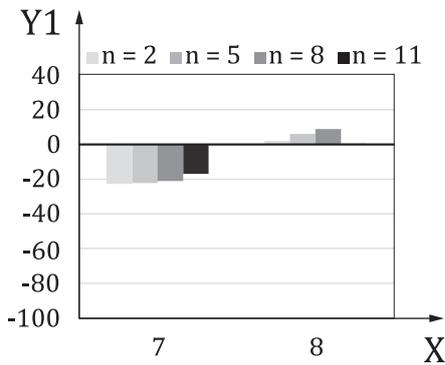
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Table A.2 — Example test report

Cutting conditions		<ul style="list-style-type: none"> — Machining centre: — Test date: — Test piece: <ul style="list-style-type: none"> — Material: — Nominal dimensions of the topmost square: — Number of sets (default: 4): — Warm-up cycle: — Cutting tool: <ul style="list-style-type: none"> — Diameter: — Length: — Number of teeth: — Material, coating: — Cutting parameters: <ul style="list-style-type: none"> — Feed speed: — Spindle speed: 					
Geometric errors of the finished test piece							
Object and references to the drawing		Measured values (position errors in mm, angular errors in ratio (mm/1 000 mm))				Major error causes (for the machine tools with B'- and C'-axes in the workpiece side, see Figure A.6)	
		Set 1	Set 2	Set 3	Set 4		
		Finished time (min)					
			0	60	120	180	
1st step of each set	1	Position error in Y of $S_{n,1,s}$ to $S_{1,1,s}$	--	(n = 4)	(n = 7)	(n = 10)	Offset in Y position
	2	Position error in X of $S_{n,4,s}$ to $S_{1,4,s}$	--	(n = 4)	(n = 7)	(n = 10)	Offset in X position
	3	Perpendicularity of $S_{n,4,s}$ to $S_{n,1,s}$	(n = 1)	(n = 4)	(n = 7)	(n = 10)	Squareness of Y- to X-axis
	4	Position error in Z of $S_{n,1,b}$ to $S_{1,1,b}$	--	(n = 4)	(n = 7)	(n = 10)	Offset in Z position
	5	Parallelism in ZX plane of $S_{n,1,b}$ to $S_{1,1,b}$ (rotation B)	--	(n = 4)	(n = 7)	(n = 10)	Change in X-axis direction around Y-axis
	6	Parallelism in YZ plane of $S_{n,2,b}$ to $S_{1,2,b}$ (rotation A)	--	(n = 4)	(n = 7)	(n = 10)	Change in Y-axis direction around X-axis
2nd step of each set	7	Position error in Y of $S_{n,3,s}$ to $S_{n,1,s}$	(n = 2)	(n = 5)	(n = 8)	(n = 11)	Position error of C'-axis in Y
	8	Position error in X of $S_{n,4,s}$ to $S_{n,2,s}$	(n = 2)	(n = 5)	(n = 8)	(n = 11)	Position error of C'-axis in X
	9	Parallelism in XY plane of $S_{n,3,s}$ to $S_{n,1,s}$ (rotation C)	(n = 2)	(n = 5)	(n = 8)	(n = 11)	Angular positioning error of C'-axis at C180° to C0°
	10	Parallelism in ZX plane of $S_{n,3,b}$ to $S_{n,1,b}$ (rotation B)	(n = 2)	(n = 5)	(n = 8)	(n = 11)	Squareness error of C'- to X-axis
	11	Parallelism in ZX plane of $S_{n,4,b}$ to $S_{n,2,b}$ (rotation B)	(n = 2)	(n = 5)	(n = 8)	(n = 11)	Squareness error of C'- to Y-axis
3rd step of each set	12	Position error in Y of $S_{n,3,s}$ to $S_{n,1,s}$	(n = 3)	(n = 6)	(n = 9)	(n = 12)	Position error of B'-axis in Z and intersection error of C'- to B'-axis
	13	Position error in X of $S_{n,4,s}$ to $S_{n,2,s}$	(n = 3)	(n = 6)	(n = 9)	(n = 12)	Position error of B'-axis in Z and intersection error of C'- to B'-axis
	14	Perpendicularity of $S_{n,4,s}$ to $S_{n,3,s}$	(n = 3)	(n = 6)	(n = 9)	(n = 12)	Parallelism error B'- to Y-axis around X
	15	Position error in Z of $S_{n,4,b}$ to $S_{n,1,b}$	(n = 3)	(n = 6)	(n = 9)	(n = 12)	Position error of B'-axis in X
	16	Parallelism in YZ plane of $S_{n,4,b}$ to $S_{n,2,b}$ (rotation A)	(n = 3)	(n = 6)	(n = 9)	(n = 12)	Parallelism error B'- to Y-axis around Z and squareness error of C'- to B'-axis

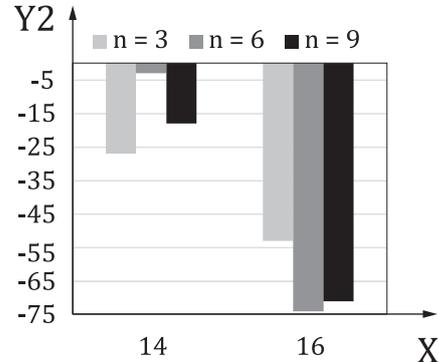
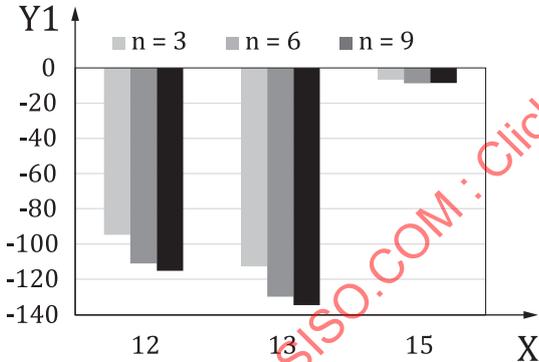


a) Position errors (#1, 2, 4; 1st step of each set) b) Angular errors (#3, 5, 6; 1st step of each set)



c) Position errors (#7, 8; 2nd step)

d) Angular errors (#9, 10, 11; 2nd step)



e) Position errors (#12, 13, 15; 3rd step)

f) Angular errors (#14, 16; 3rd step)

Key

n see [Table A.2](#)
 X evaluation item number

Y1 position error (μm)
 Y2 angular error ($\mu\text{m}/\text{m}$)

NOTE Evaluation item numbers are shown in [Table A.2](#).

Figure A.11 — Example graphical presentation of test results

A.5 Machining test to evaluate the distortion of machining centres with rotary axis (axes)

A.5.1 Test objective

This test is applicable to all machining centres with three linear axes and at least one rotary axis parallel to tool spindle. The test objective is to check the change in the accuracy in all three translational directions when heat is continuously generated by any axis, including the spindle, for a given period of time. The test is an extension of the M4 test in ISO 10791-7:2020 and the thermal test piece introduced by Wiessner et al.^[10] and the alternation of the design presented by Blaser et al.^[11].

A.5.2 Test procedure and the geometric definition of the test piece

A.5.2.1 General

[Figure A.12](#) and [Figure A.13](#) show the nominal geometry of the finished test piece.

The part blank should be placed concentric to the axis of the rotary table and to machine the final test piece should be machined in the same setup as the part blank, shown in [Figure A.16](#).

The nominal geometry is an example only. It can be modified based on an agreement between the manufacturer/supplier and user. The number of facets (F) and surface (S) can be increased based on the agreement between the manufacturer/supplier and user, which can facilitate the observation of the velocity of thermal changes, or the approach to a thermal steady state.

Depending on the test piece's size or shape, it can show faster reaction to environmental changes, e.g. thermal change due to opening or closing of the machine tool door. The influence can result in different test results when the test piece is much larger than in [Figure A.14](#).

Thermal influence on the finished test piece geometry can be significantly dependent on the machine tool configuration. The number of the measurement facets and surface and the warm-up time interval (60 min by default) can be modified depending on the machine tool configuration.

The manufacturer/supplier and user may agree on a certain warm-up cycle before the test, corresponding to particular requirements. If agreed, the test may be started without any warm-up cycle (cold start).

A cylindrical end mill with diameter 10 mm, or a corner radius end mill of the same diameter, should be used, but a different tool may be used based on an agreement between the manufacturer/supplier and user.

Depending on the diameter of the used tool, the amount of measurement surfaces (S_z) can decrease or increase. The test piece shown in [Figure A.14](#) is designed, so that with a cylindrical end mill with diameter 10 mm 10 surfaces can be manufactured, 2 reference and 8 measurement surfaces. An overlap of 0,6 mm should be used to avoid significant burr.

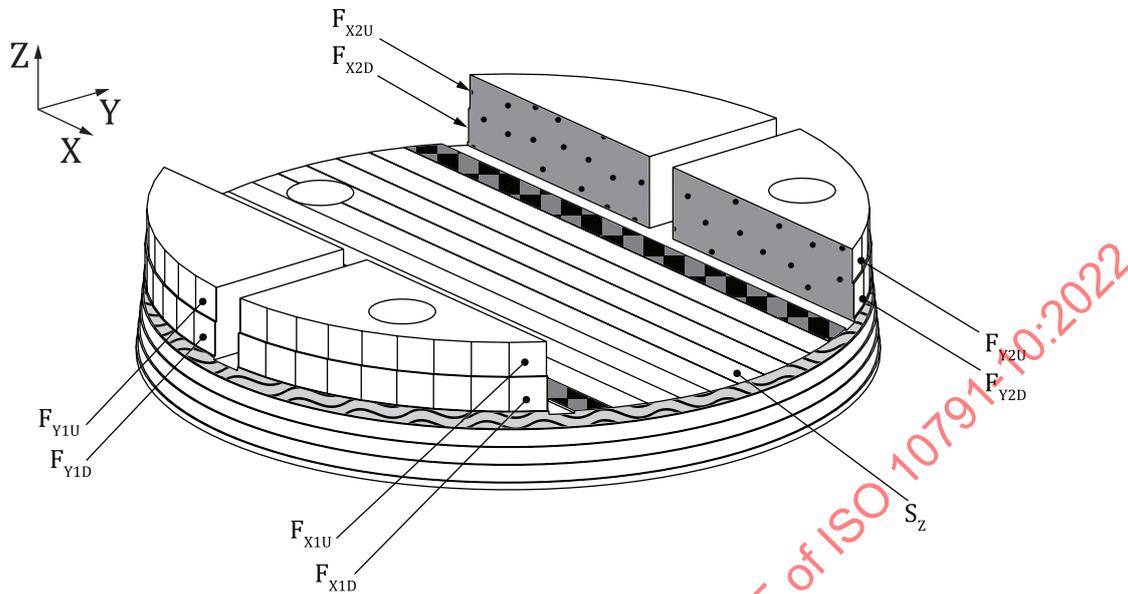
The orientation of the test piece should be marked on the top surface for the recognition of its orientation in the measurement.

Cutting fluid applied should represent the typical application of the machine tool under test. If no typical application is defined for the machine tool under test, all the machining tests should be performed without cutting fluid (dry cut), or with the minimum quantity lubrication (MQL), although cutting fluid may be used based on an agreement between the manufacturer/supplier and user.

In [Figure A.12](#) the measurement surface perpendicular to the Z-axis of the machine tool is represented by S_z . The facets of the thermal test piece are located on four different segments and on different heights. Each set of facets is represented by F_{jkl} , where:

— $j = X$ or Y , corresponding measurement direction of the facets;

- $k = 1$ or 2 , indicates sequence of milled facets;
- $l = U$ or D , indicates Z position of the group of facets (U=up, D=down).



NOTE Grey (patterned) finished surfaces to define workpiece coordinate system for the inspection on a CMM.

Figure A.12 — Finished test piece geometry with measurement surface (S) and facets (F)

For the evaluation of the thermal test piece with a coordinate measuring machine (CMM), several features are milled to define the workpiece coordinate system. The surfaces used for definition of the coordinate system are illustrated in [Figure A.12](#). The two most outer measurement surfaces (checkerboard) are used to define the X-Y-plane of the workpiece coordinate system. The vertical flanks of the large pre-milled notch (dots) are used to define the orientation of the X-coordinate. The origin of the coordinate system is determined by measuring the milled circular surface (waves) and computing its centre.

A.5.2.2 Machining sequence

The thermal test piece is designed for a test cycle that is based on eight periods of thermal load changes. For example, the day-night cycle of environmental influences over 24 hours can be evaluated by an around-the-clock test with cycle times of 4 h. Or the thermal test piece can be used for a 4 h warm-up phase, according to ISO 230-3:2020, and a 4 h cool-down phase. For the milling operations during the test-cycle a new finishing end mill made of solid tungsten carbide with a diameter of 10 mm should be used. Since the removed volume during the test-cycle is very small, the tool wear is not considered in the evaluation.

The test sequence starts with milling the reference surfaces and facets (checkerboard) as illustrated in [Figure A.13](#). The two $S_{Zn}(t_0)$ surfaces should be machined firstly to minimize the impact of the thermal expansion of the spindle on this operation. Afterwards the upper facets (F_{jkUn}) should be milled in a similar manner as illustrated in [Figure A.15](#), by rotating the table (default 6° between facets) and moving one linear axis. Afterwards the circular surfaces of the test piece should be milled by positioning the tool twice on the X-axis respectively on the Y-axis and rotating the machine tool table by at least 360° . Finalized is this step by milling the lower four reference facets ($F_{jkD}(t_0)$).

Milling the reference surfaces and facets is followed by milling the measurement surfaces and facets, as illustrated in [Figure A.13](#) in waves. One full cutting cycle is illustrated in [Figure A.15](#). The Z position of

the milling tool is not changed during the whole cycle to minimize the influence of the positioning error of the Z-axis.

- a) Step 1: The tool is positioned in the waiting position (square, Key 1). With the fixed Z-position the tool starts to mill the first $S_z(t_i)$ surface removing material at a recommended nominal depth of cut of 0,1 mm by moving in positive X-direction.
- b) Step 2 and step 3: The rotary table of the machine tool is positioned, so that with a movement in negative Y direction the first facet of the thermal test piece, the F_{X1} facet is milled.
- c) Step 4 and step 5: The machine tool table is rotated again, so that with an axis movement in negative X-direction the F_{Y1} facet is milled.
- d) Step 6 to 9: Facets F_{X2} and F_{Y2} are milled similar to the previous steps.
- e) Step 10: After the milling operations, the tool moves back to the waiting position and waits for the next milling cycle.

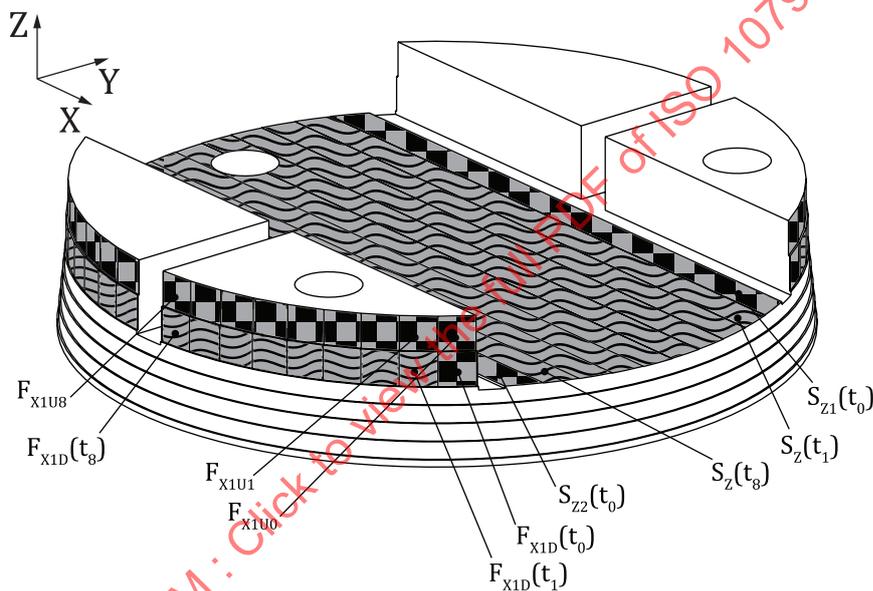


Figure A.13 — Finished test piece geometry with highlighted reference (checkerboard) and measurement surfaces (waves)