INTERNATIONAL STANDARD

ISO 230-12

First edition
2022-06

Test code for machine tools —

Part 12:
Accuracy of finished test pieces

Code d'essai des machines-outils —

Partie 12: Exactitude des pièces d'essai finies

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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*.

A list of all parts in the ISO 230 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

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

When a machine tool is used to repeatedly machine a single test piece in a mass production line, some machine tool users want to test cut that single test piece and check its geometric accuracy, as a part of acceptance tests for a machine tool. For machines machining multiple types of test pieces, standard test pieces should be used. The geometric error of the finished test piece can be caused by various error motions of a spindle, linear axes, rotary axes, or other mechanical components of a machine tool. A proper set of machining tests should be chosen such that it exhibits the influence of machine error motions for a machine tool user's possible machining applications. This document specifies a set of machining tests that can be used to assess the influence of various quasi-static error motions of a machine tool. This document is intended to supply minimum requirements for assessing the finish-cutting accuracy of the machine.

Standard test pieces are defined in machine-specific International Standards. In some machine-specific International Standards, recent machining applications are not be fully covered. For example, five-axis machining centres can perform turning operations by using a rotary table. The machine-specific International Standard for a machining centre, ISO 10791-7, describes no machining test for turning operation. Turning tests are included in ISO 13041-5. This document describes a family of machining tests that covers potential applications of various types of machine tools.

In general, machining tests described in machine-specific international standards, influenced by multiple causes, are not intended to identify individual error sources contributing to the measured errors of the machined test pieces. In contrast, tests for identifying quasi-static error motions described in ISO 230-1 are designed to identify individual error sources for each motion axis. This document provides test pieces for machining tests to isolate certain error sources and allow manufacturers/users to pick those corresponding to their intended machining applications.

The tests described in this document can be used either for testing different types of machine tools (type testing) or testing individual machine tools for acceptance purposes.

Test code for machine tools —

Part 12:
Accuracy of finished test pieces

1 Scope

This document specifies methods for defining machining tests for manufacturing accurate test pieces, and for evaluating the influence of quasi-static geometric errors of linear axes and rotary axes, and the influence of the synchronization error of simultaneously controlled multiple axes. Although quasi-static geometric errors are often major contributors for geometric errors of finished test pieces, other factors, e.g. the dynamic contouring error, can also have significant influence.

This document describes examples of test piece geometry applicable to individual machine tools, possible contributors to machining error, deviations to be measured and measuring instruments. By clarifying possible contributors to machining error in each machining test, this document gives a guidance to machine tool manufacturers or users such that proper machining tests can be chosen to evaluate a machine tool's machining performance in specified machining applications.

Machining tests to evaluate the geometric accuracy of a single surface are described in Clause 5, and those to evaluate geometric relationship of multiple machining features are described in Clause 6. Clause 7 presents machining tests for other objectives: machining tests for evaluation of short-term capability (7.2), and machining tests for evaluation of thermal influence (7.3).

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 1101:2017, *Geometrical product specifications (GPS) — Geometrical tolerancing — Tolerances of form, orientation, location and run-out*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 230-1:2012 and ISO 1101:2017 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 but in some cases, micro-radians or arc-seconds can be used for clarification purposes. Formula (1) should always be considered:

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

Temperatures are expressed in degrees Celsius (°C).

4.2 Reference to ISO 230-1

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 Machining conditions

In principle, the machining tests described in this document shall be machined under conditions that are typical for the use of the machine tool under test. If no typical use is defined, and to recognize significant errors of the machine tool under test from the geometric accuracy of the finished test piece, the tests should be performed under the following conditions:

a) machine tool axes shall be moved slowly to minimize dynamic effects and behave in a quasi-static manner, i.e. with no dynamic influences and servo [control] limitations. However, this provision is not applicable to some machine tool-specific test pieces execution (e.g. five-axes contouring test pieces) where the aim is to test machine performances at specified tool path feed speed;

b) the machine tool and the cutting tool should not be influenced by any significant machining forces, which is the case for most finishing cuts;

c) the cutting tool and the cutting parameters, i.e. feed, speed, tool geometry, etc., should be suitable for the material machined;

d) the material machined should be uniform, i.e. the change in its parameters like hardness and strength over the machined surface should be within the prescribed tolerance;

e) the cutting tool used should not be worn and should not wear significantly during the machining of the test pieces;

f) for the tests described in Clauses 5 and 6, the machine tool should not be influenced by any thermal load, i.e. the machine tool should be in a thermally stable condition. The influence of the environmental thermal change, the spindle rotation, rotating axes, and the linear motion of components, can be checked by the tests described in ISO 230-3:2020. 7.3 describes machining tests to check the thermal influence on the geometric accuracy of the finished test piece.

Although quasi-static geometric errors of a machine tool are major contributors, it is always possible that other factors, e.g. the dynamic contouring error, can impose significant influence on the finished test piece's geometry.

4.4 Tests to be performed

When testing a machine, it is by no means necessary or possible to carry out all the tests described in this document. When the tests are required for acceptance purposes, it is up to the user to choose, in agreement with the manufacturer/supplier, those tests relating to the components and/or the properties of the machine which are of interest. These tests are to be clearly stated when ordering a machine. Mere reference to this document for the acceptance tests, without specifying the tests to be

carried out, and without agreement on the relevant expenses, cannot be considered as binding for any contracting party.

In principle, no more than one piece of each type should be machined for acceptance purposes. In case of special requirements, such as statistical assessment of the machine tool performance (see 7.2), the machining of more test pieces is required.

4.5 Measuring instruments

Measuring instruments indicated in the tests described in the following sections are examples only. Other instruments capable of measuring the same quantities and having the same, or a smaller, measurement uncertainty can be used. Reference shall be made to ISO 230-1:2012, Clause 5, which indicates the relationship between measurement uncertainties and the tolerances.

When a "linear displacement sensor" is referred to, it can mean not only dial test indicators (DTI), but any type of linear displacement sensor such as analogue or digital dial gauges, linear variable differential transformers (LVDTs), linear scale displacement gauges, or non-contact sensors, when applicable to the test concerned (see ISO 230-1:2012, Clause 4).

In the same way, when a "squareness reference artefact" is mentioned, it can mean e.g. a granite or ceramic or steel or cast-iron square, a cylinder square, a reference cube, or, again, a special, dedicated artefact.

4.6 Location of test pieces

Test pieces shall be machined in the general location where production parts are machined. If no general location is specified for the machine tool under test, the test piece should be placed approximately at mid-travel of the X-axis, and in positions along Y- and Z-axes suitable for the location of the test piece and/or fixture, and for the tool lengths if not specified otherwise in the test procedure.

4.7 Fixing of test pieces

The test piece shall be conveniently mounted on a proper fixture, such that maximum stability of cutting tools and fixture is achieved. The mounting surfaces of the fixture and of the test piece shall be flat. A suitable means of fixturing should be used to allow for tool breakthrough and full-length machining of a centre hole, for example. The test piece should also be mounted on the fixture with countersink/counterbored screws, such that subsequent machining does not interfere with the screws. Other methods are possible and may be selected. The overall height of the test piece depends on the selected method of fixing. Fixtures used for machining are preferably used also for measurements.

4.8 Material of test pieces, tooling and cutting parameters

The test piece material, tooling and the subsequent cutting parameters are subject to agreement between manufacturer/supplier and user and shall be recorded. The test piece material shall be specified with proper material designations.

Machine-specific International Standards specify the size of test pieces. If not, it is subject to agreement between manufacturer/supplier and user.

4.9 Rough cuts

This document does not specify roughing operations. Preliminary cuts should be taken in order to make the depth of cut as constant as possible.

4.10 Diagrams

Diagrams in this document illustrate only an example test setup. The coordinate system, and the name of axes, depicted in diagrams are also only examples.

4.11 Information to be recorded

For tests made according to the requirements of this document, the following information shall be compiled as completely as possible and included in the test report. Additional information to be reported is described in each test.

a) material and designation of the test piece;

b) material, dimensions, and number of teeth of the tool;

c) cutting speed(s);

d) feed speed(s);

e) depth(s) of cut;

f) other cutting parameters, e.g. cutting fluid;

g) position and orientation of the test piece in the work space;

h) direction of cuts (where applicable);

i) measuring instrument and method;

j) measurement uncertainty with coverage factor k = 2.

4.12 Software compensation

When software facilities are available for compensating geometric, thermal or dynamic 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 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 Machining tests to evaluate the geometric accuracy of a single surface

5.1 General

Clause 5 specifies a set of machining tests, whose objective is to finish a single surface and to evaluate its geometric accuracy. The main objective of the tests is to observe the influence of quasi-static error motions, as well as position and orientation errors of axis average lines, of linear axes, rotary axes, or a spindle.

This clause does not specify drilling tests. The position accuracy of a drilled hole is often influenced by many factors other than the machine's geometric errors.

5.2 Machining of a cylindrical surface

5.2.1 Machining of rotating disc

5.2.1.1 Object

A cylindrical surface of a rotating test piece is machined. It is typically a turning operation with a non-rotating tool. It may be the cylindrical grinding with a rotating wheel. The circularity of the machined cylindrical surface is evaluated (see Table 1).

Table 1 — Machining of a rotating disc

Inputs			Outputs	Major error contributors for machining in Figure 1
No. of simultaneous linear motions during machining	No. of simultaneous rotary motions during machining	Type of interpolation	Geometric features to be measured	Radial error motion of (C')-axis, $E_{X(C')}$
1 (Z)	1 (C')	—	Roundness	Tilt error motion of (C')-axis, $E_{B(C')}$
	or 2, if a rotating tool is used.			Radial and tilt error motion of tool-holding spindle axis, if a rotating tool is used.

The geometric errors observed in this test can be also observed in the test in 5.2.2. When the machine tool under test is used for the machining of not only thin ring parts but also cylindrical parts, the test in 5.2.2 should be carried out.

5.2.1.2 Test procedure

A cylindrical surface of a rotating test piece is machined by feeding a non-rotating tool (or a rotating wheel) to the axial direction of spindle (Z) (see Figure 1).
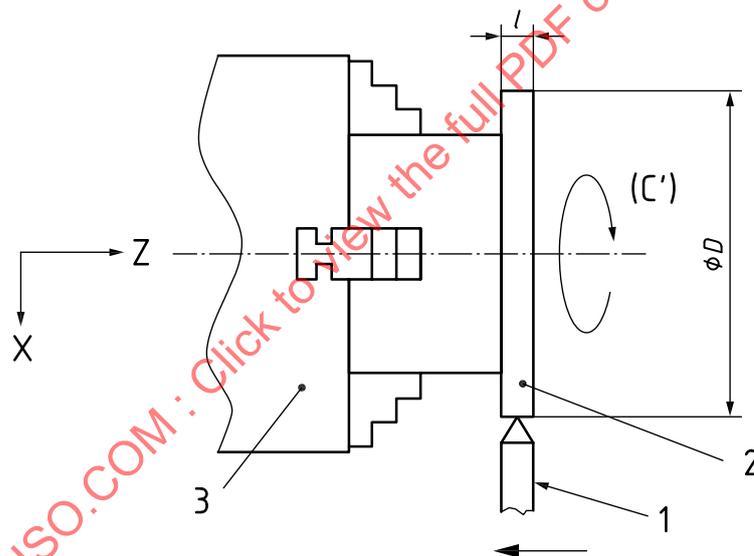
Key

1	cutting tool	l	width of the cylindrical surface
2	test piece	D	diameter of the cylindrical surface
3	machine chuck		

Figure 1 — Machining of a rotating disc

The width of the cylindrical surface, l, should be chosen to suit the measuring instrument. The roundness shall be measured at middle of the width of the cylindrical surface.

5.2.1.3 Geometric features to be measured

The roundness of the finished cylindrical surface.

5.2.1.4 Measuring instrument

A roundness measuring machine.

5.2.1.5   Possible contributors to machining error

The radial error motion of a workholding spindle (C') is the main contributor to the roundness of the finished surface. Its tilt error motion can contribute as well, and its influence is typically proportional to the distance from the chuck face to the machining position.

The contribution of the straightness error motion of the linear axis (Z) is negligibly small.

On machine tools with rotating tool spindle, radial and tilt error motions of tool spindle influence the test result.

5.2.1.6   Machines to be tested

— Machine tools that finish a rotating test piece by turning operations, e.g. turning machines and turning centres, and a machining centre with a rotary table with turning capability;

— cylindrical grinding machines.

5.2.1.7   Information to be reported

— The nominal diameter of the finished cylindrical surface, *D*;

— the width of the cylindrical surface, *l*;

— the distance from the chuck jaw face to the machining position;

— spindle speed and feed speed.

NOTE   Details for machining parameters are shown in ISO 13041-6, ISO 1708 and ISO 2433.

5.2.2   Machining of rotating cylinder with a feed in the axial direction

5.2.2.1   Object

A cylindrical surface of a rotating test piece is machined by feeding a non-rotating tool in a turning operation, or a rotating wheel in a cylindrical grinding operation, to the axial direction of the spindle (Z). Unlike the test in 5.2.1, three-dimensional geometry of the finished test piece is evaluated (see Table 2).

Table 2 — Machining of a cylindrical surface with a feed in the axial direction

Inputs			Outputs	Major error contributors for machining in Figure 2
No. of simultaneous linear motions during machining	No. of simultaneous rotary motions during machining	Type of interpolation	Geometric features to be measured	Tilt error motions of (C')-axis, $E_{B(C')}$, Radial error motion of (C')-axis, $E_{X(C')}$
1 (Z)	1 (C') or 2, if a rotating tool is used.	—	Cylindricity. The cylindricity may be estimated by the roundness and the consistency of diameters. Roundness at different Z positions	Parallelism error of (C')- to Z-axis, $E_{B(0Z)}$ (C'). Straightness error motion of Z-axis, E_{XZ}. For a rotating tool: Radial and tilt error motion of tool spindle. Tool spindle axis of rotation not parallel to Z. Conical grinding wheel

5.2.2.2 Test procedure

A cylindrical surface of a rotating test piece is turned by feeding a non-rotating tool to the axial direction of the spindle (Z) [see Figure 2 a)]. The length of the finished cylinder, *L*, is typically the diameter of the finished test piece multiplied by 0,8 to 2,5, depending on the chucking of the test piece or the orientation of the spindle axis (vertical or horizontal). Figure 2 b) shows the setup on a cylindrical grinding machine.
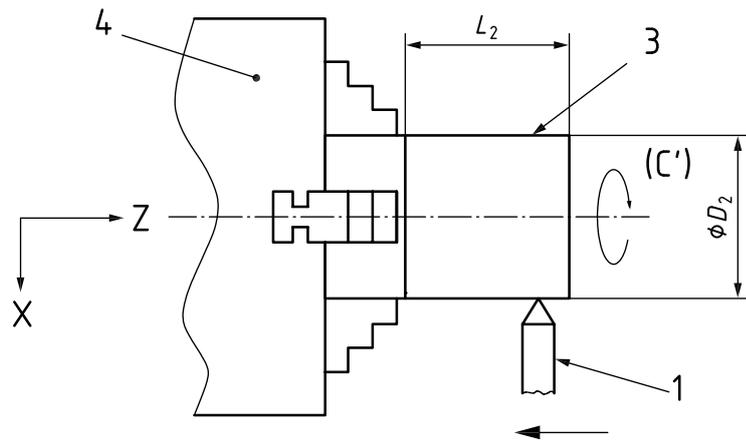
a) Turning by a non-rotating cutting tool
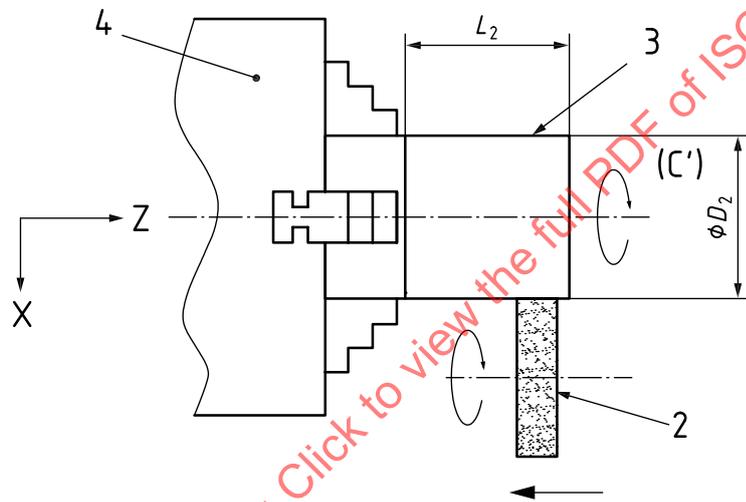
b) Grinding by a grinding wheel

Key

1	cutting tool	D_2	diameter of the finished cylinder
2	grinding wheel	L_2	length of the finished cylinder
3	test piece		
4	machine chuck		

Figure 2 — Machining of a cylindrical surface with a feed in the axial direction

5.2.2.3 Geometric features to be measured

— The roundness of the finished cylindrical surface at two different axial (Z) positions;

— the cylindricity of the finished test piece (see ISO 12180-1). The cylindricity may be estimated by the roundness and the consistency of diameters machined at different Z positions.

5.2.2.4 Measuring instruments

— Roundness measuring machine;

— coordinate measuring machine (CMM);

— outside/inside micrometer to measure the consistency of diameters.

5.2.2.5 Possible contributors to machining error

See 5.2.1.5 for contributors to the roundness at each axial position (Z).

The difference in the roundness at two axial positions (Z) shows the influence of the tilt error motion of the spindle (C'). Its influence is proportional to the distance between two measured positions.

The parallelism error of the linear axis (Z) and the spindle axis (C') makes the finished test piece conical. It causes the inconsistency of the diameter at different axial (Z) positions, which increases the cylindricity error of the finished test piece. Another contributor to the cylindricity error of the finished test piece is the straightness error motion of the Z-axis in the radial (X) direction.

When a rotating tool is used, radial and tilt error motions of tool spindle, a conical grinding wheel, and a spindle of rotating tool not parallel to the Z-axis of machine tool, can contribute.

5.2.2.6 Analogous tests

An internal cylindrical surface of a rotating test piece is turned by feeding a non-rotating boring tool to the axial direction of the spindle (Z) (see Figure 3). Contributors to the machining error are analogous to those in the test above. In a boring operation, angular error motions of the linear axis, e.g. E_{BZ}, can have larger influence on the cylindricity of the finished test piece due to the larger offset in Z.

Key

1   cutting tool
2   test piece
3   machine chuck
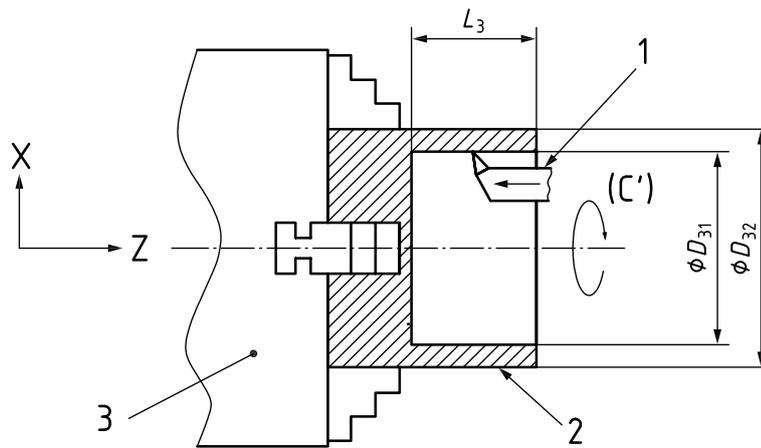
D_{31} diameter of the finished inner cylinder
D_{32} outer diameter of the cylinder
L_3 length of the finished inner cylinder

Figure 3 — Machining of an internal cylindrical surface with a feed in the axial direction

Alternatively, three discs can be machined (see Figure 4). The three-disc surfaces are treated as pertaining to a single cylinder. The roundness of the three-disc surfaces and the consistency of their diameters are evaluated, respectively the cylindricity of the three discs combined.

Key
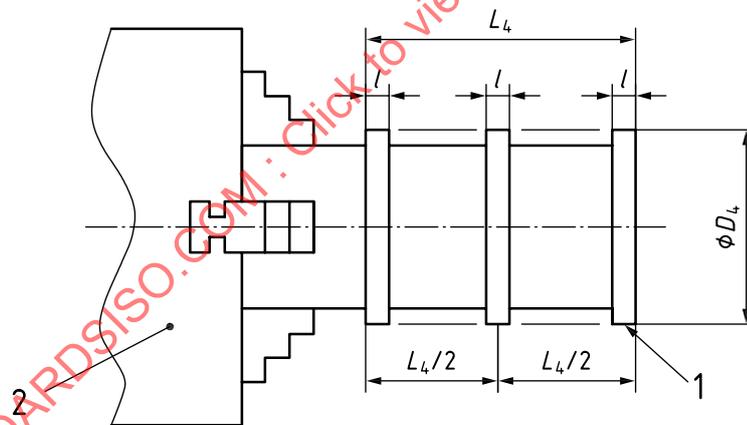
1   test piece
2   machine chuck

L_4 total length of the cylinder
l width of single disc
D_4 diameter of disc

Figure 4 — Machining of three discs with a feed in the axial direction

5.2.2.7   Machines to be tested

— Machine tools that finish a rotating test piece by turning operations, e.g. turning machines and turning centres, and a machining centre with a rotary table with turning capability;

— internal and external cylindrical grinding machines.

5.2.2.8 Information to be reported

— The nominal diameter of the finished surface;

— the width of the cylindrical surface, (L_2 in Figure 2, L_3 in Figure 3 and L_4 in Figure 4);

— the width of the discs, l (in Figure 4 only);

— the nominal diameter of the unfinished surface, D_{32} (in Figure 3 only);

— spindle speed and feed speed.

NOTE   Details for machining parameters are shown in ISO 13041-6, ISO 1708 and ISO 2433.

5.2.3   Machining of a cylindrical surface by circular contouring

5.2.3.1   Object

A cylindrical surface is machined by a rotating tool moving on a circular trajectory by two linear axes. The roundness error of the finished surface is measured (see Table 3). Table 3 shows an example for circular contouring in the XY plane.

Table 3 — Machining of a cylindrical surface by circular contouring by X- and Y-axes

Inputs			Outputs	Major error contributors for machining in Figure 5
No. of simultaneous linear motions during machining	No. of simultaneous rotary motions during machining	Type of interpolation	Geometric features to be measured	Straightness error motions, E_{YX} and E_{XY}, and linear positioning error motions, E_{XX} and E_{YY}. Squareness error of Y to X, $E_{C(0X)Y}$.
2 (X and Y)	1 (Tool)	Circular	Roundness	Angular error motions, E_{AX}, E_{BX}, E_{CX}, E_{AY}, E_{BY}, and E_{CY}, can influence depending on the machine configuration and the positions where linear positioning and straightness error motions are measured. Radial error motions of the spindle (C) and tilt error motions of the spindle (C), $E_{X(C)}$, $E_{Y(C)}$, $E_{A(C)}$, and $E_{B(C)}$. Dynamic errors caused by circular interpolation and different following errors (mismatch of position loop gains).

5.2.3.2   Test procedure

The surface is finished on a circular trajectory by two linear axes (see Figure 5).

The blank shall be provided with a base suitable for being fastened to the work holding table/pallet or to a fixture, providing a sufficient stiffness. Preliminary cuts should be taken to make the depth of cut as constant as possible.

Key
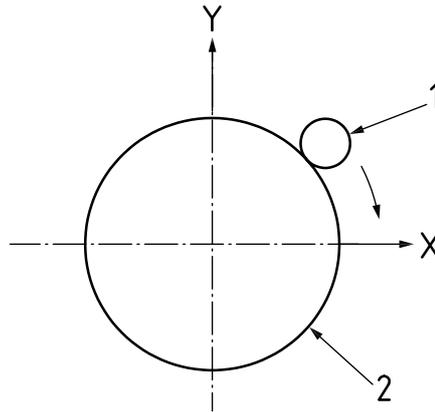
1   cutting tool   2   test piece

Figure 5 — Machining test of a cylindrical surface by circular contouring

5.2.3.3   Geometric features to be measured

The roundness of the finished surface, including start/stop and reversal points.

5.2.3.4   Measuring instrument

A roundness-measuring machine or coordinate measuring machine (CMM).

5.2.3.5   Possible contributors to machining error

The straightness error motion, the linear positioning error motion of the linear axes (X and Y), the squareness error of Y to X, and the radial error motion of the spindle are the main contributors.

The angular error motions (pitch and roll) of the linear axes (X and Y) and the tilt error motion of the spindle (C) can also influence the roundness. Their influence can be larger in proportion to the tool length and/or test piece setting position. The yaw error motion of linear axes can influence the roundness depending on the machine configuration and the position where the straightness error motion is measured.

The dynamic contouring error with circular interpolation of X and Y axes influences the roundness error, e.g. the quadrant glitch.

The ingoing or outgoing of the cutter can influence the roundness profile of the surface.

5.2.3.6   Machines to be tested

— Machine tools that finish a surface by a rotating spindle, e.g. all milling machines, and NC grinding machines for grinding operations;

— wire electrical discharge machining (EDM) machines.

5.2.3.7   Information to be reported

— Tool length and diameter and number of teeth, or diameter of grinding wheel, if applicable;

— spindle speed and feed speed, if applicable;

— radial and axial depth of cut;

— diameter of test piece.

NOTE   Details for machining parameters are shown in ISO 10791-7, ISO 8636-1, ISO 1985 and ISO 14137.

5.3   Machining tests of a flat surface

5.3.1   Facing of a rotating test piece

5.3.1.1   Object

A surface perpendicular to the spindle axis (C') is machined by feeding a cutting tool to the radial direction of the spindle axis (C'). Typically, it is a turning process with a non-rotating tool. It can be done by using a rotating grinding wheel. The flatness of the machined surface is evaluated (see Table 4).

Table 4 — Facing of a rotating test piece

Inputs			Outputs	Major error contributors for machining in Figure 6
No. of simultaneous linear motions during machining	No. of simultaneous rotary motions during machining	Type of interpolation	Geometric features to be measured	Axial and tilt error motions of (C')-axis, $E_{ZC(C')}$ and $E_{B(C')}$
1 (X)	1 (C') or 2 if a rotating tool is used	—	Flatness	Squareness error of (C')- to X-axis, $E_{B(0X)(C')}$. Straightness error motion of X-axis, E_{ZX}. Angular error motion, E_{BX}, can influence depending on the machine configuration and the position where the straightness error motion is measured. When a rotating tool is used, axial and tilt error motions of tool spindle. In the configuration shown in Fig. 6c, the radial error motion of tool spindle can also influence.

5.3.1.2   Test procedure

A surface perpendicular to the spindle axis (C') is turned by feeding a non-rotating tool to the radial direction of the spindle axis (C') [see Figure 6 a)]. Figures 6 b) and c) show the test setup on a cylindrical grinding machine.

a) Facing by a non-rotating tool

b) Facing by a grinding wheel

c) Facing by a tilted grinding wheel
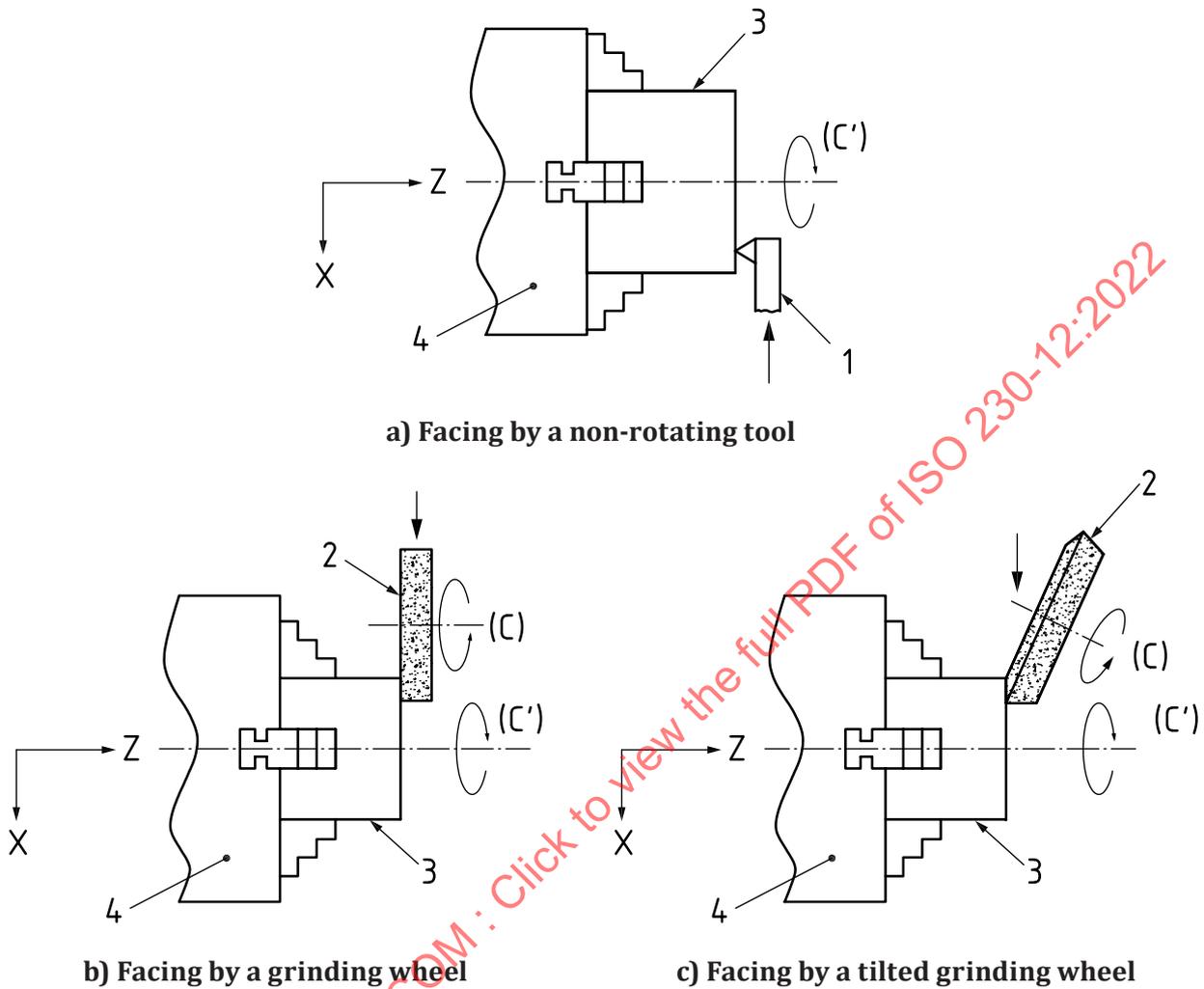
Key

1	cutting tool	3	test piece
2	grinding wheel	4	machine chuck

Figure 6 — Facing of a rotating test piece

5.3.1.3 Geometric features to be measured

The flatness of the finished surface.

5.3.1.4 Measuring instruments

Coordinate measuring machine (CMM), or linear displacement sensor and surface plate.

5.3.1.5 Possible contributors to machining error

The axial error motion of a work-holding spindle (C') is the major contributor to the flatness of the finished surface.

When the spindle (C') has the fundamental face error motion, the finished face can be viewed as made up of many flat-faced thin rings, each of which is out-of-square with the axis of rotation by an amount, which increases with decreasing radius. If the part is mounted in a roundness-measuring machine with the transducer sensing axially, then the part can be tilted so that no flatness error is sensed during a trace around a circular path concentric with the part centre. Circular flatness measurements need a combination with straightness measurement over the full diameter. For details, see ISO 230-7:2015, A.7.6.

The tilt error motion of the spindle (C') can contribute as well, and its influence is proportional to the distance from the axis of rotation to the measured position.

The straightness error motion of the linear axis (X) also has direct influence on the flatness of the finished surface.

The squareness error of the linear axis (X) to the spindle axis of rotation (C') results in a conical geometry of the finished surface.

The angular error motion of X-axis, E_{BX}, can influence depending on the machine configuration and the position where the straightness error motion is measured.

5.3.1.6   Machines to be tested

— Machine tools that finish a rotating test piece by turning operations, e.g. turning machines and turning centres, and a machining centre with a rotary table with turning capability;

— cylindrical grinding machines.

5.3.1.7   Information to be reported

— The nominal diameter of the raw material;

— the distance from the chuck face to the finished surface;

— spindle speed and feed speed.

NOTE   Details for machining parameters are shown in ISO 13041-6.

5.3.2   Machining of a flat surface with non-rotating test piece

5.3.2.1   Object

A flat surface is machined by rotating a tool moving on a linear trajectory by a single linear axis. It is typically the face milling by using a rotating milling cutter or the surface grinding by using a rotating grinding wheel. The flatness error of the finished surface is measured (see Table 5). Table 5 shows an example for the feed to the X-direction.

Table 5 — Machining of a flat surface with non-rotating test piece

Inputs			Outputs	Major error contributors for machining in Figure 7
No. of simultaneous linear motions during machining	No. of simultaneous rotary motions during machining	Type of interpolation	Geometric features to be measured	Straightness error motion of X-axis in Z-direction and angular error motions, E_{ZX}, E_{AX}, and E_{BX}. The squareness error of spindle (C) to X-axis, $E_{B(0X)(C)}$.
1 (X)	1 (Tool)	—	Flatness	When multiple paths are machined at different Y positions, straightness and angular error motions of Y-axis, E_{ZY}, E_{AY}, E_{BY} as well as the squareness error of spindle (C) to Y-axis, $E_{A(0(C))Y}$
				Axial error motion of the spindle (C) and tilt error motions of the spindle (C), $E_{Z(C)}$, $E_{A(C)}$ and $E_{B(C)}$.
				Conical grinding wheel.

5.3.2.2 Test procedure

The surface is finished on a linear trajectory by a single linear axis. This test should be subsequently performed by two bidirectional cuts (see Figure 7).

The blank shall be provided with a base suitable for being fastened to the work holding table/pallet or to a fixture, providing a sufficient stiffness. Preliminary cuts should be taken to make the depth of cut as constant as possible.

Dimensions in millimetres

Key
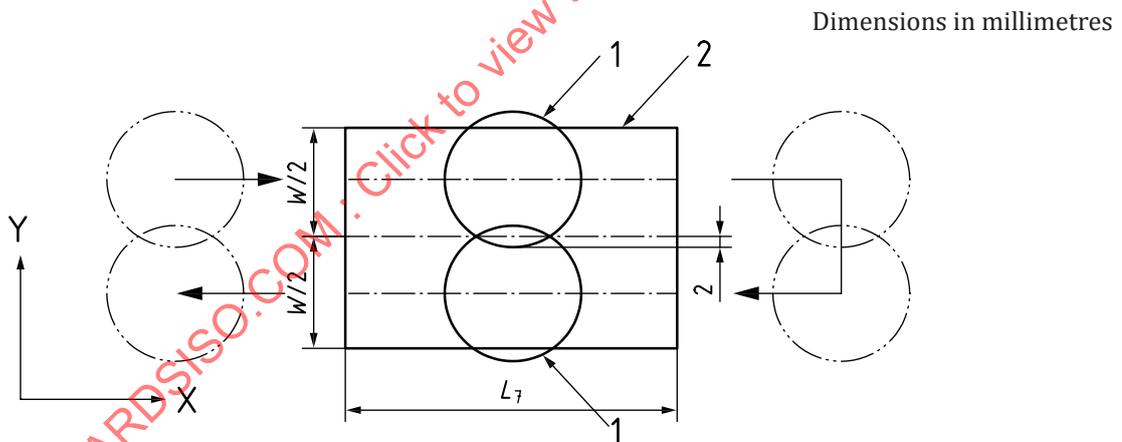
1   cutting tool
2   test piece
L_7 length of test piece
W width of test piece

Figure 7 — Machining of a flat surface with non-rotating test piece

5.3.2.3 Geometric features to be measured

The flatness of the finished surface.

5.3.2.4 Measuring instruments

— Linear displacement sensor, gauge blocks, straightness reference artefact, or surface plate;

— coordinate measuring machine (CMM).

5.3.2.5 Possible contributors to machining error

The straightness error motion of the linear axis (X) in the tool's axial direction (Z-direction) and the axial error motion of the spindle are the main contributors.

The angular error motions (pitch and roll) of the linear axis (X) and the tilt error motion of the spindle (C) can also influence the flatness. The squareness error of the spindle (C) to the X-axis, $E_{B(0X)(C)}$, also influences the flatness. Their influence can be larger in proportion to the tool diameter.

When multiple paths are machined at different Y positions, straightness and angular error motions of Y-axis, namely E_{ZY}, E_{AY}, E_{BY}, also affect the flatness. The squareness error of the spindle (C) to the Y-axis, $E_{A(0Y)(C)}$, also influences the flatness.

The ingoing or outgoing of the cutter possibly influences the straightness profile in the feed direction (X).

A conical grinding wheel influences the flatness.

5.3.2.6 Machines to be tested

Machine tools that finish a flat surface by a rotating spindle, e.g. all milling machines, and surface grinding machines for grinding operations.

5.3.2.7 Information to be reported

— Diameter and number of teeth of milling tool or diameter of grinding wheel;

— spindle speed and feed speed;

— axial depth of cut;

— width W and length L_7 of test piece.

NOTE   Details for machining parameters are shown in ISO 10791-7, ISO 8636-1 and ISO 1985.

5.3.3 Face machining of multiple surfaces

5.3.3.1 Object

The surface of rectangular test pieces, fixed at multiple locations on the machine table, is finished by a rotating tool moving on a linear trajectory by a single linear axis. The variation in the thickness of test pieces machined at different positions is measured (see Table 6 and Figure 8).

Table 6 — Face machining of multiple surfaces

Inputs			Outputs	Major error contributors for machining in Figure 8
No. of simultaneous linear motions during machining	No. of simultaneous rotary motions during machining	Type of interpolation	Geometric features to be measured	Straightness error motion of X-and Y-axes, E_{ZX} and E_{ZY}.
1 (X)	1 (Tool)	—	The variation in the thickness of test pieces	Angular error motion of X-and Y-axes, E_{BX} and E_{AX}, E_{AY} and E_{BY}.
				Parallelism error of the machine table surface to X- and Y-axes

5.3.3.2 Test procedure

The test pieces are suggested to be located as follows:

— one at the central point of the table;

— one at each of the four corners of the table.

The test pieces should be of equal hardness and should be suitably fixed to the table.

The top surface of the single test piece is finished on a linear trajectory by a single linear axis (X) at the same Z height. Between the single test pieces the Y-axis may be moved.
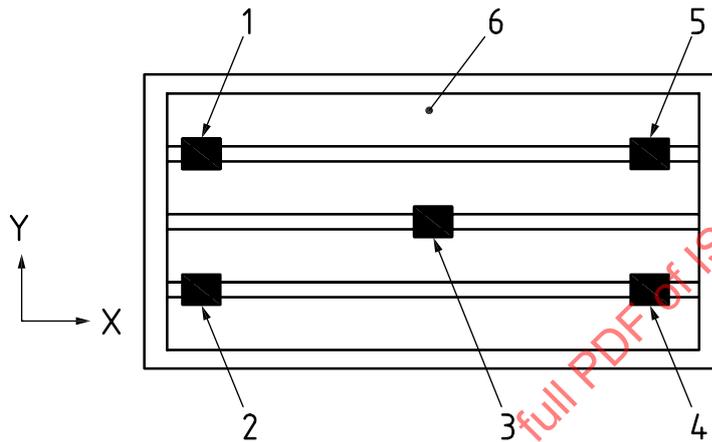
Key
1-5   test piece
6   machine table

Figure 8 — Face machining of multiple surfaces

5.3.3.3   Geometric features to be measured

The variation in the thickness of test pieces.

5.3.3.4   Measuring instruments

Linear displacement sensor or thickness tester or coordinate measuring machine (CMM).

5.3.3.5   Possible contributors to machining error

The straightness error motions of the two linear axes (X and Y) in the tool's axial direction (Z-direction) are the main contributors. The test allows to check the straightness deviation at two discrete locations over the entire workspace.

The difference in the thickness of the two test pieces at the same X position, for example, shows the variation in the local parallelism error of the table surface to the Y-axis.

The angular error motions of the two linear axes (pitch and roll of X and Y axes) can be a major contributor. Their influence can be larger in proportion to the tool diameter.

Prior to the machining test, the parallelism of the machine table surface to X- and Y-axes should be checked. It can be a dominant contributor to the test result.

The axial error motion and the tilt error motion of the spindle (C) can influence the flatness of each test piece but has negligibly small influence on the variation in the thickness of test pieces.

When the Z-axis (the axis in the tool's axial direction) is not moved in the machining test, its linear positioning error does not influence the test result.

5.3.3.6   Machines to be tested

Machine tools that finish a surface by a rotating spindle, e.g. all milling machines, and NC grinding machines for grinding operations;

NOTE   Details for machining parameters are shown in ISO 8636-1 and ISO 1985.

5.3.4   Flank machining with one linear axis

5.3.4.1   Object

A flat surface is machined by a rotating tool moving on a linear trajectory by a single linear axis. The straightness error of the finished surface is measured (see Table 7 and Figure 9). Table 7 shows an example for the feed to the X-direction.

It can be also machined by the EDM process.

Table 7 — Flank machining with one linear axis

Inputs			Outputs	Major error contributors for machining in Figure 9
No. of simultaneous linear motions during machining	No. of simultaneous rotary motions during machining	Type of interpolation	Geometric features to be measured	Straightness error motion in Y-direction and roll error motion of X-axis, E_{YX} and E_{AX}.
1 (X)	1 (Tool)	—	Straightness	Radial error motion of the spindle (C) in Y-direction and tilt error motion of the spindle (C) around X-axis, $E_{Y(C)}$ and $E_{A(C)}$.
				The angular error motion of X-axis can influence depending on the machine configuration and the position where the straightness error motion is measured.

5.3.4.2   Test procedure

The surface is finished on a linear trajectory by a single linear axis (see Figure 9).

The blank shall be provided with a base suitable for being fastened to the work holding table/pallet or to a fixture providing a sufficient stiffness. Preliminary cuts should be taken to make the depth of cut as constant as possible.

Key
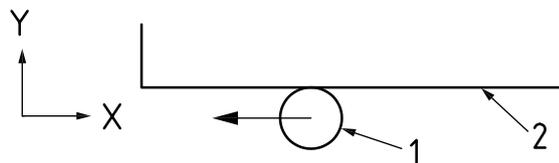
1   cutting tool

2   test piece

Figure 9 — Flank machining with one linear axis

5.3.4.3   Geometric features to be measured

The straightness of the finished surface along the feed direction.

5.3.4.4   Measuring instruments

Straightness reference artefact, gauge blocks, linear displacement sensor or coordinate measuring machine (CMM).

5.3.4.5   Possible contributors to machining error

The straightness error motion of the linear axis (X) in the tool's radial direction (Y-direction) and the radial error motion of the spindle are the main contributors. For wire EDM machines, there is no spindle influence.

The angular error motions (roll) of the linear axis (X) and the tilt error motion of the spindle (C) can also influence the straightness. Their influence can be larger in proportion to the tool length and/or test piece setting position.

The yaw error motion of X-axes can influence depending on the machine configuration and the position where the straightness error motion is measured.

5.3.4.6   Machines to be tested

— Machine tools that finish a flat surface by a rotating spindle, e.g. all milling machines, and surface grinding machines for grinding operations;

— wire EDM machines.

5.3.4.7   Information to be reported

— Tool length and diameter and number of teeth, or diameter of grinding wheel, if applicable;

— spindle speed and feed speed, if applicable;

— radial and axial depth of cut, if applicable;

— length of test piece.

NOTE   Details for machining parameters are shown in ISO 10791-7, ISO 8636-1 and ISO 1985.

5.3.5   Flank machining with two linear axes

5.3.5.1   Object

A flat surface is machined by a rotating tool moving on a linear trajectory by two linear axes. The straightness error of the finished surface is measured (see Table 8).

It can be also machined by the EDM process.

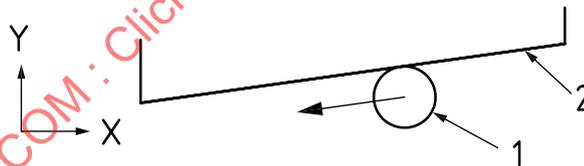**Table 8 — Flank machining with two linear axes**

Inputs			Outputs	Major error contributors for machining in Figure 10
No. of simultaneous linear motions during machining	No. of simultaneous rotary motions during machining	Type of interpolation	Geometric features to be measured	Straightness error motions and angular error motions, E_{YX}, E_{XY}, E_{AX}, E_{BX}, E_{AY} and E_{BY}.
2 (X and Y)	1 (Tool)	Linear	Straightness	Linear positioning error motions, E_{XX}, E_{YY}. Influence of straightness and positioning error motions of each axis depends on angle of machined surface. Radial error motions of the spindle (C) and tilt error motions of the spindle (C), $E_{X(C)}$, $E_{Y(C)}$, $E_{A(C)}$ and $E_{B(C)}$. Dynamic contouring error of linear interpolation. Stick slip of Y-axis (for side face tilted by 3°)

5.3.5.2 Test procedure

The surface is finished on a linear trajectory by two linear axes. The side face is tilted by 3° or by 45° from a linear axis (see Figure 10). It shall be finished by a single path. The start and stop points shall be outside of the test piece to avoid the influence of the acceleration and the deceleration on the machined surface.

The blank shall be provided with a base suitable for being fastened to the work holding table/pallet or to a fixture, providing a sufficient stiffness. Preliminary cuts should be taken in order to make the depth of cut as constant as possible.

Key
1 cutting tool
2 test piece

Figure 10 — Flank machining with two linear axes

5.3.5.3 Geometric features to be measured

The straightness of the finished surface along the feed direction.

5.3.5.4 Measuring instruments

Straightness reference artefact, gauge blocks, linear displacement sensor or coordinate measuring machine (CMM)

5.3.5.5 Possible contributors to machining error

The straightness error motion of the linear axes (X and Y) in the tool's radial direction (X- and Y-direction) and the radial error motions of the spindle are the main contributors. For wire EDM machines, there is no spindle influence.

The side face tilted by 3° can show the influence of the stick-slip of the linear axis with smaller motion (Y-axis).

The angular error motions (pitch and roll) of the linear axes (X and Y) and the tilt error motions of the spindle (C) can also influence the straightness. Their influence can be larger in proportion to the tool length and/or test piece setting position.

The ingoing or outgoing of the cutter can influence the straightness profile of the surface.

5.3.5.6 Machines to be tested

— Machine tools that finish a flat surface by a rotating spindle, e.g. all milling machines, and surface grinding machines for grinding operations;

— wire EDM machines.

5.3.5.7 Information to be reported

— Tool diameter and number of teeth, or diameter of grinding wheel, if applicable;

— spindle speed and feed speed, if applicable;

— radial and axial depth of cut, if applicable;

— length of test piece;

— tool length, if applicable.

NOTE   Details for machining parameters are shown in ISO 10791-7, ISO 8636-1 and ISO 1985.

5.4   Machining of a rotating spherical surface

5.4.1   Object

A spherical surface is rotated by spindle (C') and machined by circular interpolation of two linear axes (Z and X). The roundness is measured along an arc in the ZX plane (see Table 9).

Table 9 — Machining of a rotating spherical surface

Inputs			Outputs	Major error contributors for machining in Figure 11
No. of simultaneous linear motions during machining	No. of simultaneous rotary motions during machining	Type of interpolation	Geometric features to be measured	Error in circular interpolation in ZX plane.
2 (Z and X)	1 (C')	Circular	Roundness	Radial, axial and tilt error motions of (C')-axis, $E_{X(C')}$, $E_{Z(C')}$ and $E_{B(C')}$. Error motions of X and Z axis, as well as squareness between X- and Z-axes and the parallelism between (C')- and Z-axes, E_{XX}, E_{ZX}, E_{BX}; E_{ZZ}, E_{XZ}, E_{BZ}; $E_{B(0Z)X}$, $E_{B(0Z)(C')}$

5.4.2   Test procedure

A rotating spherical surface is machined by circular interpolation of two linear axes (Z and X) (see Figure 11).

The roundness is measured over the 100° measurement range in continuous measuring mode starting at position A and finishing at position B. Positions A and B are shown in Figure 11. The hemisphere pole is not included in the measured arc.

Key
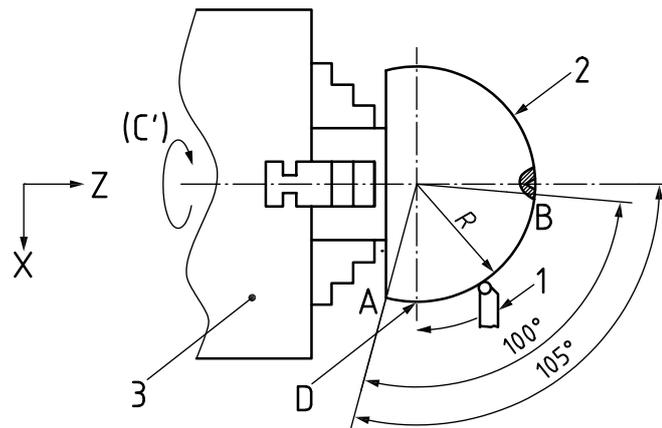
1	cutting tool	R	radius of sphere
2	test piece	A, B	end points of measured arc
3	machine chuck	D	a point on the spherical surface at the same Z and Y positions with the centre

Figure 11 — Machining of a rotating spherical surface

5.4.3 Geometric features to be measured

The roundness along the arc A-B.

5.4.4 Measuring instruments

— Coordinate measuring machine (CMM);

— roundness measuring machine.

5.4.5 Possible contributors to machining error

Both radial and axial error motions of the spindle (C') influence the roundness. The region near point A is influenced more by radial and tilt error motions of (C')-axis, $E_{X(C')}$ and $E_{B(C')}$, while the region near point B is influenced more by the axial error motion of (C')-axis, $E_{Z(C')}$.

The contouring error in the circular interpolation of Z- and X-axes directly influences the roundness of the finished test piece. The squareness error of X- to Z-axes can increase the roundness error, although its influence is minor on the arc over 100°. The parallelism error of Z-axis to the spindle axis (C') also gives small influence.

The quadrant glitch in the circular interpolation can be observed at point D.

Linear positioning, straightness and angular error motions of X- and Z-axes, E_{XX}, E_{ZX}, E_{BX}, E_{ZZ}, E_{XZ} and E_{BZ}, also influence the roundness.

5.4.6 Machines to be tested

Machine tools that finish a rotating test piece by turning operations, e.g. turning machines and turning centres, and a machining centre with a rotary table with turning capability.

5.4.7 Information to be reported

— The nominal diameter of the finished surface;

— spindle speed and feed speed.

NOTE   Details for machining parameters are shown in ISO 13041-6.

5.5   Flank milling of a cone frustum with five-axis interpolation

5.5.1   Object

Checking the cutting performance of five-axis machining centres under the five-axis simultaneous feed motion by machining the cone shaped test piece with a flank milling tool (see Table 10).

Table 10 — Flank milling of a cone frustum with five-axis interpolation

Inputs			Outputs	Major error contributors
No. of simultaneous linear motions during machining	No. of simultaneous rotary motions during machining	Type of interpolation	Geometric features to be measured	Potentially all the error motions of five axes, as well as position and orientation errors of rotary axis average lines, can influence the roundness. The sensitivity of the roundness to each error motion depends on the machine configuration or the test setup.
3 (X, Y, and Z)	3 (Two rotary axes and a tool)	Five-axis	Roundness	Dynamic error with simultaneous five-axis motion can also influence the roundness.

5.5.2   Test procedure

The surface is finished by the five-axis simultaneous feed motion (see Figure 12). This test is applicable only to five-axis machine tools with two rotary axes (see Figure 13 for an example test setup).

The test piece should be fixed on the table with the inclination angle to the table surface to ensure simultaneous five-axis motion. When the test is performed on a five-axis machine with one or more rotary axes on the workpiece side, the bottom centre of the test piece should have a centre offset distance from the rotary axis average line(s).

The outer surface of the frustum shall be machined by a flank milling tool. The tip of the cutter shall move on a circular path at constant speed in the workpiece coordinate system.

A ring-shaped flat surface shall be machined on the top surface of the test piece as the reference for the measurement. It shall be machined by the same cutting tool used for the finishing. It shall be machined by driving linear axes only, with rotary axes fixed.

The blank shall be provided with a base suitable for being fastened to the work holding table/pallet or to a fixture, providing a sufficient stiffness. Preliminary cuts should be taken in order to make the depth of cut as constant as possible.

Key
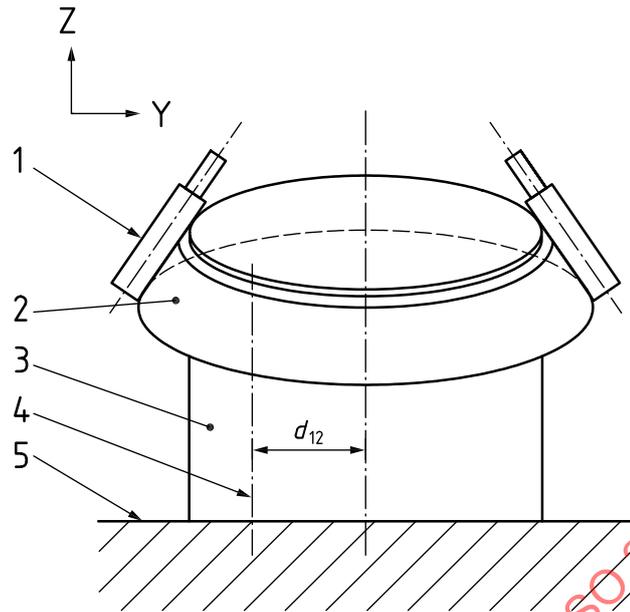
1   cutting tool
2   test piece
3   fixture
4   axis average line of rotary table
5   rotary table
d_{12} centre offset distance from rotary axis average line

Figure 12 — Flank milling of a cone frustum with five-axis interpolation
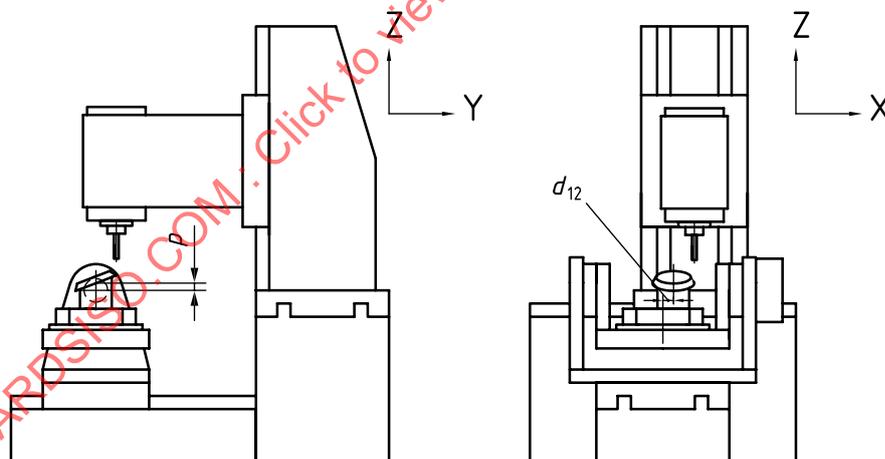
Key

d_{12} offset from C'-axis in X direction
p offset from A'-axis in Z direction

Figure 13 — Example cone frustum machining test setup

5.5.3   Geometric features to be measured

The roundness of the finished surface at two different heights (e.g. at 2mm from top and from bottom) in the workpiece coordinate system.

5.5.4   Measuring instruments

A roundness measuring machine or coordinate measuring machine (CMM).

5.5.5 Possible contributors to machining error

Potentially all the error motions of five axes can influence the roundness. The sensitivity of the roundness to each error motion depends on the machine configuration or the test setup. In particular, position errors of rotary axis average lines often have larger influence on the roundness.

If the two rotary axes are on the workpiece side, the positioning error of the Z-axis is of no influence.

Dynamic error with simultaneous five-axis motion can also influence the roundness.

5.5.6 Machines to be tested

Machine tools that can perform simultaneous five-axis motion for machining, e.g. five-axis machining centres and turning centres with a swivelling tool-holding spindle.

NOTE   Details for machining parameters are shown in ISO 10791-7.

5.6 Flank milling of a truncated square pyramid with five-axis interpolation

5.6.1 Object

Checking the cutting performance of five-axis machining centres under the five-axis simultaneous feed motion by machining the truncated square pyramid test piece with flank milling (see Table 11 and Figure 14).

Table 11 — Flank milling of a truncated square pyramid with five-axis interpolation

Inputs			Outputs	Major error contributors
No. of simultaneous linear motions during machining	No. of simultaneous rotary motions during machining	Type of interpolation	Geometric features to be measured	Potentially all the error motions of five axes, as well as position and orientation errors of rotary axis average lines, can influence the straightness of each machined surface. The sensitivity of the straightness to each error motion depends on the machine configuration or the test setup.
3 (X, Y, and Z)	3 (Two rotary axes and a tool)	Five-axis	Straightness	Dynamic error with simultaneous five-axis motion can also influence the straightness.

5.6.2 Test procedure:

The surface is finished by the five-axis simultaneous feed motion. This test is applicable only to five-axis machine tools with two rotary axes (see Figure 14 for an example test setup).

The test piece should be fixed on the table with the inclination angle to the table surface to ensure simultaneous five-axis motion.

The side faces of the truncated square pyramid shall be machined by a flank milling tool. The cutter path shall be straight at constant speed in the workpiece coordinate system.

The blank shall be provided with a base suitable for being fastened to the work holding table/pallet or to a fixture, providing a sufficient stiffness. Preliminary cuts should be taken in order to make the depth of cut as constant as possible.
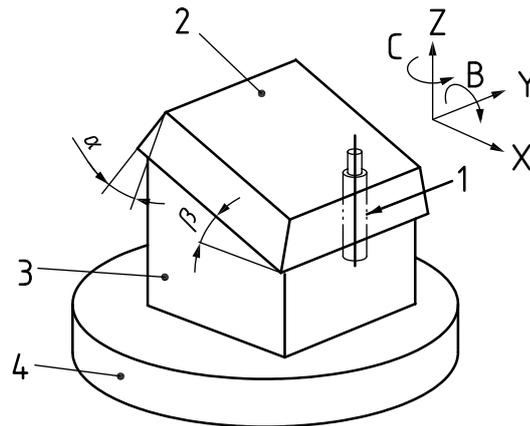
Key

1	cutting tool	4	rotary table
2	test piece	α	half of pyramid angle
3	fixture	β	inclination angle of test piece

Figure 14 — Flank milling of a truncated square pyramid with five-axis interpolation

5.6.3 Geometric features to be measured

The straightness of the finished surface.

5.6.4 Measuring instruments

Straightness reference artefact, gauge blocks, linear displacement sensor or coordinate measuring machine (CMM)

5.6.5 Possible contributors to machining error

Potentially all the error motions of five axes can influence the straightness. The sensitivity of the straightness to each error motion depends on the machine configuration or the test setup. In particular, position errors of rotary axis average lines often have larger influence on the straightness.

Dynamic error with simultaneous five-axis motion can also influence the straightness.

5.6.6 Machines to be tested

Machine tools that can perform simultaneous five-axis motion for machining, e.g. five-axis machining centres and turning centres with a swivelling tool-holding spindle.

6 Machining tests to evaluate geometric relationship of multiple machining features

6.1 General

This clause specifies a set of machining tests, whose objective is to finish multiple machining features and to evaluate the position or the orientation of one feature relative to other features, or the difference in their geometric accuracy. Main objective of the tests is to observe the influence of quasi-static error motions, as well as position and orientation errors of axis average lines, of linear axes, rotary axes or a spindle.

6.2 Machining of internal and external cylindrical surfaces

6.2.1 Object

With reference to Figure 15, the inner hole is machined by rotating the workholding spindle (C'-axis) only. The external cylindrical surface is machined by synchronizing the workholding spindle (C'-axis) and a linear axis (X-axis). True position of the external cylindrical surface relative to the centre of the inner hole (datum A) is measured (see Table 12).

Table 12 — Machining test of inner and external cylindrical surfaces

Inputs			Outputs	Major error contributors for machining in Figure 15
No. of simultaneous linear motions during machining	No. of simultaneous rotary motions during machining	Type of interpolation	Geometric features to be measured	Position error of workholding spindle (C'-axis). Error in X-C interpolation
Inner hole: 1 (Z) External cylindrical surface: 2 (Z and X)	1 (C')	XC interpolation	Position of external cylindrical surface in reference to the inner hole Roundness of external cylindrical surface	

6.2.2 Test procedure

The inner hole is machined by rotating the test piece (C'-axis). The external cylindrical surface is machined by synchronizing the workholding spindle (C'-axis) and a linear axis (X-axis) at slower speed (see Figure 15). It is typically a turning process with a non-rotating tool. Cylindrical grinding can be applied. When the test is done by X-axis, the cutting point shall be at the same Y position as the C'-axis centreline.
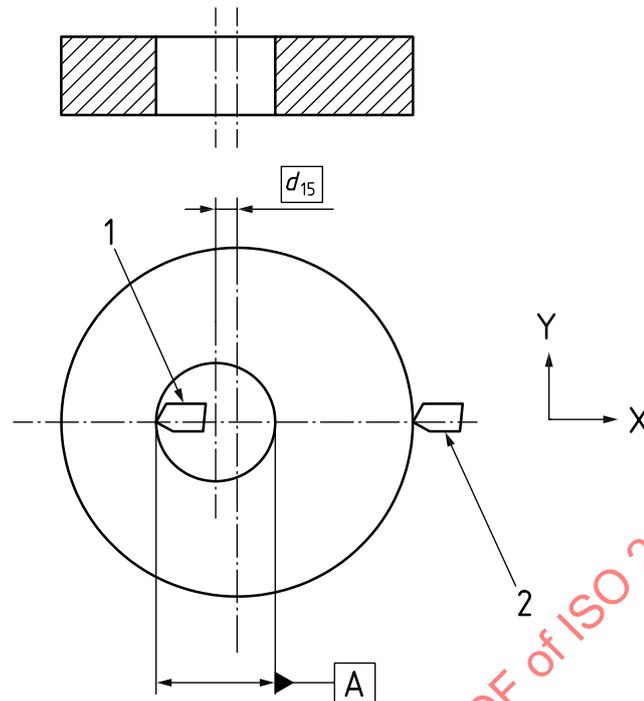
Key

1, 2 cutting tool

d_{15} distance between the centre of the hole and the centre of the external cylinder

Figure 15 — Test piece for machining of inner and external cylindrical surfaces

6.2.3   Geometric features to be measured

— The position of the external cylindrical surface relative to the axis of the inner cylinder (datum A);

— roundness of external cylindrical surface

6.2.4   Measuring instruments

— Coordinate measuring machine (CMM) for the position error of the external cylindrical surface.

— roundness measuring machine or CMM for the roundness of the external cylindrical surface.

6.2.5   Possible contributors to machining error

The position error of the axis average line of the workholding spindle (C'-axis).

The setting error of cutting point position (e.g. setting error of tool length) can also impose significant influence.

Error in X-C interpolation, including the linear positioning error of X-axis in the synchronous operation and the radial error motion of the workholding spindle (C'-axis), can influence the test result.

6.2.6   Machines to be tested

Machine tools that finish a rotating test piece by turning operations, e.g. turning centres, turning machines equipped with numerically controlled C-axis, a machining centre with a rotary table with turning capability and a cylindrical grinding machine with a rotary table.

6.2.7 Information to be reported

— The nominal diameter of the inner hole and the external cylindrical surface, the nominal distance between their centres;

— the distance from the chuck face to the centre of the finished cylindrical surface;

— spindle speed and feed speed.

NOTE   Details for machining parameters are shown in ISO 13041-6.

6.3 Machining of holes at multiple positions over the test piece

6.3.1 Object

Finish holes at multiple positions on a test piece by e.g. boring operations. The position error of the centre of holes relative to the defined positions is measured (see Table 13).

Table 13 — Multiple holes

Inputs			Outputs	Major error contributors for machining in Figure 16
No. of simultaneous linear motions during machining	No. of simultaneous rotary motions during machining	Type of interpolation	Geometric features to be measured	Positioning error motion of X- and Y-axes, E_{XX} and E_{YY}.
1 (Z)	1 (Tool)	—	The position error of the centre of holes relative to the defined positions	Straightness error motion of X- and Y-axes, E_{YX} and E_{XY}. Angular error motion of X-, Y- and Z-axes. Squareness between X and Y

6.3.2 Test procedure

The holes at four positions in a single test piece are finished by feeding a single linear axis (Z) (see Figure 16).
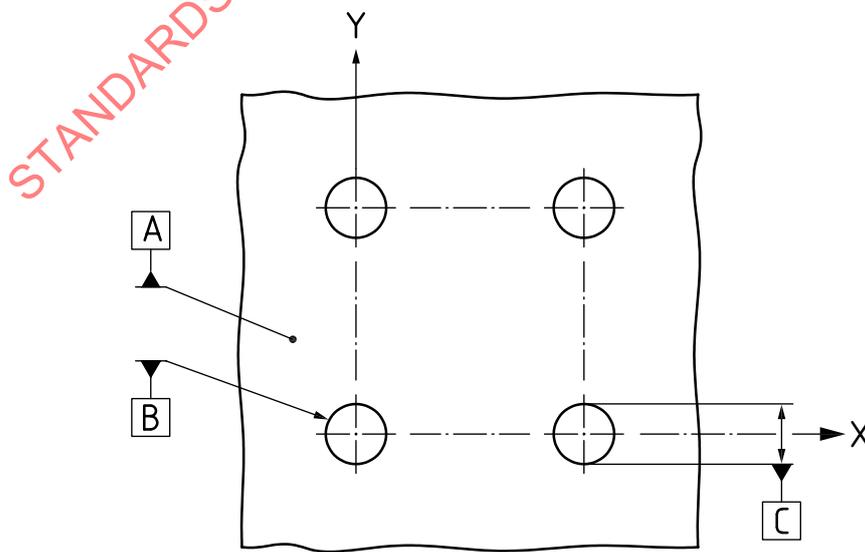

Figure 16 — Test piece with multiple holes

6.3.3 Geometric features to be measured

Position error of the centre of holes relative to the defined positions. It is measured in the following coordinate system:

— A is the primary reference. The Z axis is outgoing normal to the plane;

— Cylinder axis of datum B intersects with datum A; the intersection point is the origin; if datum B is evaluated as a circle, then the centre of the circle is projected perpendicular to datum A onto datum A and the projected centre defines the origin.

— The X-axis is the connection of the origin and the point of intersection of datum C (cylinder axis) and datum A; if datum C is evaluated as a circle, then the centre of the circle is projected perpendicular to datum A onto datum A and the connection of the projected centre of datum C and the origin defines the X-axis.

— The Y-axis is normal to X-axis and Z-axis.

6.3.4 Measuring instrument

Coordinate measuring machine (CMM).

6.3.5 Possible contributors to machining error

The X-position error of the lower-right hole shows the linear positioning deviation of X-axis at this position. The Y-position error of the upper-left hole shows the linear positioning deviation of Y-axis at this position.

The X-position error of the upper-left hole shows the squareness error between X- and Y-axes.

The position error of the upper-right hole is influenced by all these errors, as well as straightness error motions of X- and Y-axes.

The angular error motions of the linear axes (pitch, roll and yaw of X and Y axes, and E_{AZ} and E_{BZ}) can be major contributors. Their influence can depend on the test piece setting position and tool length.

The radial error motion and the tilt error motion of the spindle (C) can influence the radius and roundness of each hole but has negligibly small influence on the position error of the centre of holes.

6.3.6 Machines to be tested

Machine tools that finish a surface by a rotating spindle, e.g. all milling machines, and NC grinding machines for grinding operations.

6.4 Machining multiple surfaces with linear motion

6.4.1 Flank machining of two faces perpendicular to each other

6.4.1.1 Object

Two flat surfaces are machined by a rotating tool moving on linear trajectories by two linear axes perpendicular to each other. The perpendicularity error between the finished surfaces, as well as the straightness error of the finished surfaces, is measured (see Table 14).
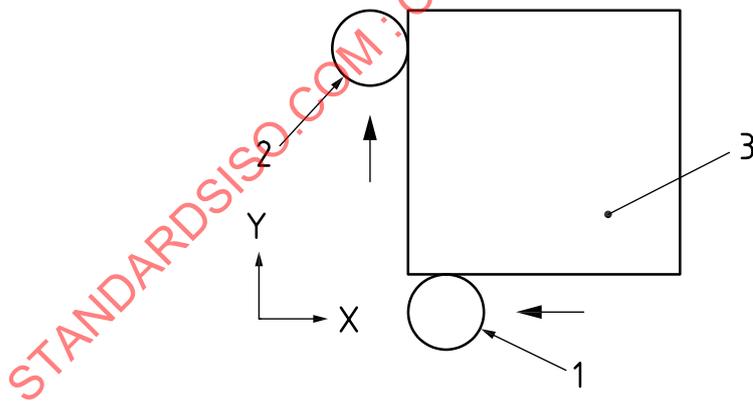
Table 14 — Flank machining of two faces perpendicular to each other

Inputs			Outputs	Major error contributors for machining in Figure 17
No. of simultaneous linear motions during machining	No. of simultaneous rotary motions during machining	Type of interpolation	Geometric features to be measured	Squareness of Y- to X-axis. Straightness error motions of X- and Y-axes, E_{YX} and E_{XY}.
1 (X or Y)	1 (Tool)	—	Perpendicularity error Straightness error	The roll error motion of X- and Y-axes, E_{AX} and E_{BY}, can influence depending on the position where the straightness error motion is measured. The yaw error motion of X- and Y-axes, E_{CX} and E_{CY}, can influence depending on the machine configuration and the position where the straightness error motion is measured. The radial and tilt error motions of the spindle (C).

6.4.1.2 Test procedure

The surfaces are finished on linear trajectories by a single linear axis (see Figure 17).

The blank shall be provided with a base suitable for being fastened to the work holding table/pallet or to a fixture, providing a sufficient stiffness. Preliminary cuts should be taken to make the depth of cut as constant as possible.

Key

1,2　cutting tool

3　　test piece

Figure 17 — Flank machining of two faces perpendicular to each other

6.4.1.3 Geometric features to be measured

— The perpendicularity error between the two finished surfaces;

— the straightness error of the two finished surfaces.

6.4.1.4   Measuring instruments

— Squareness reference artefact, or reference indexing table, and gauge blocks, surface plate, linear displacement sensor;

— coordinate measuring machine (CMM).

6.4.1.5   Possible contributors to machining error

The squareness error of the linear axes (X- and Y-axis) is the main contributor to the perpendicularity error

The straightness error motions of X- and Y-axes, E_{YX} and E_{XY}, are the main contributors to the straightness error of the two finished surfaces.

The roll error motion of X- and Y-axes, E_{AX} and E_{BY}, can influence depending on the position where the straightness error motion is measured. The yaw error motion of X- and Y-axes, E_{CX} and E_{CY}, can influence depending on the machine configuration and the position where the straightness error motion is measured.

The radial and tilt error motion of the spindle (C) and the ingoing or outgoing of the cutter can influence the straightness profile of the surface.

6.4.1.6   Machines to be tested

— Machine tools that finish a flat surface by a rotating spindle, e.g. all milling machines, and surface grinding machines for grinding operations;

— wire EDM machines.

6.4.1.7   Information to be reported

— Tool diameter and number of teeth or diameter of grinding wheel, if applicable;

— spindle speed and feed speed, if applicable;

— radial and axial depth of cut, if applicable;

— lengths of machined surfaces

NOTE   Details for machining parameters are shown in ISO 10791-7, ISO 8636-1 and ISO 1985.

6.4.2   Flank machining of faces inclined with respect to the reference surface

6.4.2.1   Test procedure

Two flat surfaces are machined by a rotating tool moving on linear trajectories by two linear axes inclined to the reference surface. The angle error relative to the defined angle, as well as the straightness error of the finished surfaces, is measured (see Table 15).
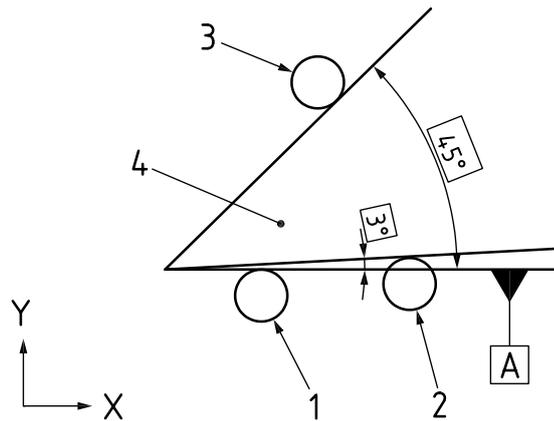
Table 15 — Flank machining of faces inclined to the reference surface

Inputs			Outputs	Major error contributors for machining in Figure 18
No. of simultaneous linear motions during machining	No. of simultaneous rotary motions during machining	Type of interpolation	Geometric features to be measured	Squareness error of Y-to X-axis.
2 (X and Y) and 1(X)	1 (Tool)	linear	Error in angle between the two finished faces. Straightness of the two finished faces.	The difference in the linear positioning error of X- and Y-axes. Straightness error motion of X-and Y-axis, E_{YX} and E_{XY}. The angular error motion of X- and Y-axes can influence depending on the machine configuration and the position where the straightness error motion is measured. Dynamic synchronous error between X-and Y-axis. Radial and tilt error motion of spindle to straightness.

6.4.2.2 Test procedure

The reference surface A is machined by feeding a tool to the X direction. At a different Z position, the surfaces, tilted by 3° and 45° from the X-axis are finished on linear trajectories by two linear axes (see Figure 18). The start and stop points shall be outside of the test piece to avoid the influence of the acceleration and the deceleration on the machined surface.

The blank shall be provided with a base suitable for being fastened to the work holding table/pallet or to a fixture, providing a sufficient stiffness. Preliminary cuts should be taken to make the depth of cut as constant as possible.

Key

1 cutting tool machining reference A
2 cutting tool machining 3° inclined surface
3 cutting tool machining 45° inclined surface
4 test piece

Figure 18 — Flank machining of two faces inclined to the reference surface

6.4.2.3 Geometric features to be measured

— Error in angle between the two finished faces (angle to reference surface);

— straightness of the two finished faces.

6.4.2.4 Measuring instruments

— Coordinate measuring machine (CMM);

— reference indexing table, surface plate, and linear displacement sensor.

6.4.2.5 Possible contributors to machining error

The squareness error of the linear axes (X- and Y-axis) contributes to an angle error. The difference in the linear positioning error of X- and Y-axes also causes an angle error. Their influence is larger on the 45° line.

The straightness error motion of the linear axes of X- and Y-axis, E_{YX} and E_{XY}, are the main contributors to the straightness error of the two finished faces. Angular error motions of X- and Y-axis, E_{AX}, E_{BX}, E_{AY} and E_{BY} can affect the result.

The side face tilted by 3° can show the influence of the stick-slip of the linear axis with smaller motion (Y-axis).

The feedback loop gain mismatch between X and Y axes can influence the straightness deviation of the face tilted by 45°.

The radial and tilt error motion of the spindle (C) and the ingoing or outgoing of the cutter can influence the straightness profile of the surface.

6.4.2.6 Machines to be tested

— Machine tools that finish a flat surface by a rotating spindle, e.g. all milling machines, and surface grinding machines for grinding operations;

— wire EDM machines.

6.4.2.7 Information to be reported

— Tool diameter and number of teeth, or diameter of grinding wheel, if applicable;

— spindle speed and feed speed, if applicable;

— radial and axial depth of cut, if applicable;

— lengths of machined surfaces.

NOTE   Details for machining parameters are shown in ISO 10791-7, ISO 8636-1 and ISO 1985.

6.5   Multiple features machined with angular indexing of test piece

6.5.1   Boring of a cylindrical surface with angular indexing of test piece by 180°

6.5.1.1   Object

A test piece is mounted on a rotary table (B'-axis). A cylindrical surface is machined from one side for its half axial length by a rotating tool. Then, the rotary table is rotated by 180°, and the cylindrical surface is machined from the other side such that both cylindrical surface are nominally coaxial. The cylindricity of the cylindrical surface is evaluated (see Table 16).

Table 16 — Boring of a cylindrical surface with angular indexing of test piece

Inputs			Outputs	Major error contributors for machining in Figure 19
No. of simultaneous linear motions during machining	No. of simultaneous rotary motions during machining	Type of interpolation	Geometric features to be measured	Angular positioning error motion of rotary table with 180° angular positioning, E_{BB}.
1 (Z)	1 (Tool)	†	Cylindricity Coaxiality	Position error of rotary table axis average line, E_{X0B}.
				Tilt error motions of rotary table with 180° angular positioning, E_{AB} and E_{CB}.
				Axial and radial error motion of B' at 0° and 180°, E_{YB} and E_{XB}
				Straightness and angular error motions of Z-axis, E_{XZ}, E_{YZ}, and E_{AZ} and E_{BZ}.
				Radial error motions of the spindle (C) and tilt error motions of the spindle (C), $E_{X(C)}$, $E_{Y(C)}$, $E_{A(C)}$, and $E_{B(C)}$.
				Squareness error of Z-axis to B'-axis, $E_{A(0B')Z}$.
				Parallelism errors of Z-axis to the spindle axis, $E_{A(0(C))Z}$ and $E_{B(0(C))Z}$.

6.5.1.2   Test procedure:

A test piece is mounted on a rotary table (B'-axis). A cylindrical surface is machined for half the axial length of the finished cylinder by a rotating tool. The centreline of the cylindrical surface is at the nominal X-position of the rotary table axis average line. Then, the rotary table is rotated by 180°, and

the cylindrical surface is machined from the other side at the same nominal X-position of the rotary table axis average line (see Figure 19).

The blank shall be provided with a base suitable for being fastened to the work holding table/pallet or to a fixture, providing a sufficient stiffness. Preliminary cuts should be taken to make the depth of cut as constant as possible.
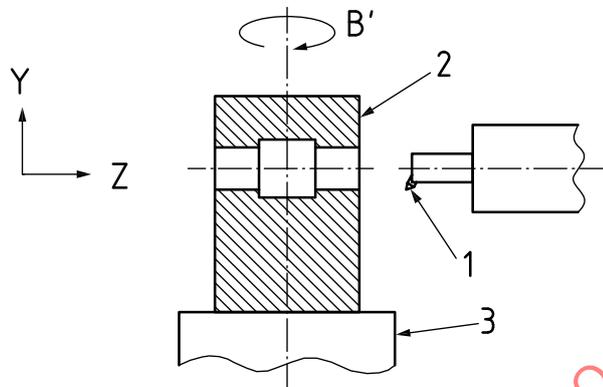
Key

1   cutting tool   3   rotary table
2   test piece

Figure 19 — Boring of a hole with angular indexing of test piece

6.5.1.3   Geometric features to be measured

The cylindricity of the cylindrical surface (see ISO 12180-1). It can be estimated by measuring roundness profiles of the machined cylindrical surface at several different positions along the axis of the cylindrical surface. Their concentricity shall be included in the evaluation.

The coaxiality of the cylindrical surfaces machined at at B' = 0° and 180°.

6.5.1.4   Measuring instruments

— A roundness measuring machine or coordinate measuring machine (CMM) to evaluate the cylindricity;

— a CMM and a roundness measuring machine with Z measurement capability to evaluate the coaxiality.

6.5.1.5   Possible contributors to machining error

When there exist the position error of rotary table axis average line, E_{X0B}, the two cylindrical surfaces, machined at B = 0° and 180°, are parallel but not coaxial to each other.

The angular positioning error motion of rotary table with 180° angular positioning, E_{BB}, results in the orientation error between the two cylindrical surfaces.

When axial error motion E_{YB} and/or radial error motion E_{XB} of the rotary table are different at 0° and 180°, the two cylindrical surfaces are parallel but not coaxial to each other.

Tilt error motion of rotary table with 180° angular positioning, E_{AB}, also results in the orientation error between the two cylindrical surfaces. Tilt error motion of rotary table with 180° angular positioning, E_{CB}, results in parallel cylindrical surfaces that are not coaxial.

Straightness error motions of Z-axis, E_{XZ} and E_{YZ}, affect the cylindricity of each part of the cylindrical surface.