
**Fine ceramics (advanced ceramics,
advanced technical ceramics) — Test
method for flexural strength of monolithic
ceramics at room temperature**

*Céramiques techniques — Méthode d'essai de résistance en flexion
des céramiques monolithiques à température ambiante*

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Foreword

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

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

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

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

ISO 14704 was prepared by Technical Committee ISO/TC 206, *Fine ceramics*.

This second edition cancels and replaces the first edition (ISO 14704:2000) and the technical corrigendum (ISO 14704:2000/Cor. 1:2004), which have been technically revised.

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Fine ceramics (advanced ceramics, advanced technical ceramics) — Test method for flexural strength of monolithic ceramics at room temperature

1 Scope

This International Standard specifies a test method for determining the flexural strength of monolithic fine ceramics, and whisker- or particulate-reinforced ceramic composites, at room temperature. Flexural strength is one measure of the uniaxial strength of a fine ceramics. This test method may be used for materials development, quality control, characterization and design data-generation purposes.

2 Normative references

The following referenced documents are indispensable for the application 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 3611:1978, *Micrometer callipers for external measurement*

ISO 7500-1:2004, *Metallic materials — Verification of static uniaxial testing machines — Part 1: Tension/compression testing machines — Verification and calibration of the force-measuring system*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1

flexural strength

maximum nominal stress at fracture of a specified elastic beam loaded in bending

3.2

four-point flexure

configuration of flexural strength testing where a specimen is loaded equally by two bearings symmetrically located between two support bearings

See Figure 1 a) and b).

NOTE The bearings may be cylindrical rollers or cylindrical bearings.

3.3

four-point-1/4 point flexure

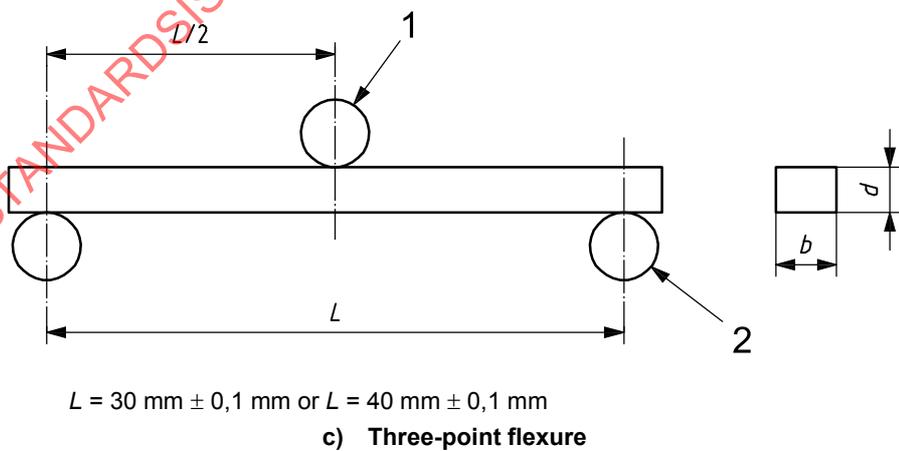
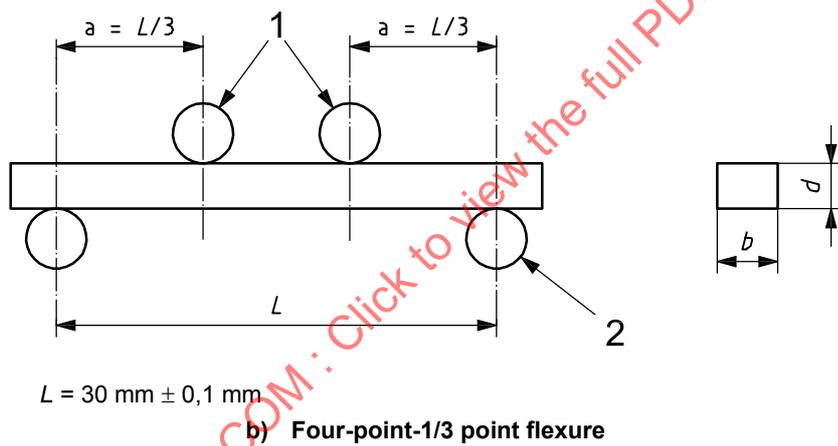
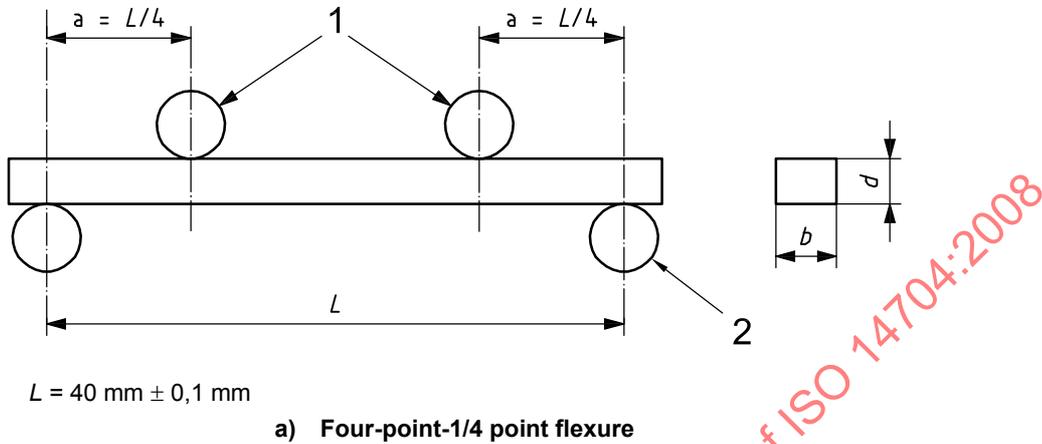
specific configuration of four-point flexural strength testing where the inner bearings are situated one-quarter of the support span away from the two outer bearings

See Figure 1 a).

3.4
four-point-1/3 point flexure

specific configuration of four-point flexural strength testing where the inner bearings are situated one-third of the support span away from the two outer bearings

See Figure 1 b).



Key

- 1 loading bearings
- 2 support bearing

Figure 1 — Flexural test configurations

3.5**semi-articulating fixture**

test fixture designed to apply uniform and even loading to test specimens that have flat and parallel surfaces

3.6**fully articulating fixture**

test fixture designed to apply uniform and even loading to specimens that may have uneven, non-parallel or twisted surfaces

3.7**three-point flexure**

configuration of flexural strength testing where a specimen is loaded at a location midway between two support bearings

See Figure 1.

NOTE Four-point flexure is usually preferred, since a large amount of material is exposed to the maximum stress (see Annex A for more information).

4 Principle

A beam specimen with a rectangular cross-section is loaded in flexure until fracture. The load at fracture, the test fixture and specimen dimensions are used to compute the flexural strength which is a measure of the uniaxial tensile strength of a ceramic. The material is assumed to be isotropic and linearly elastic.

5 Apparatus**5.1 Testing machine**

A suitable testing machine capable of applying a uniform cross-head speed shall be used. The testing machine shall be equipped for recording the peak load applied to the test piece. The testing machine shall be in accordance with ISO 7500-1:2004, Class 1, with an accuracy of 1 % of indicated load at fracture.

5.2 Test fixture**5.2.1 General**

Three- or four-point flexure configurations shall be used, as illustrated in Figure 1. The four-point-1/4 point configuration is recommended. The fixture shall have bearings that are free to roll, as described in 5.2.2, in order to eliminate frictional constraints when the specimen surfaces expand or contract during loading. In addition, the fixture shall be designed so that parts "articulate" or tilt to ensure uniform loading to the specimen. The articulation is designed so that parts of the fixture can rotate, as shown in Figure B.1, to ensure even loading on the left and right bearings. An articulation is also needed to ensure that all the bearings evenly contact the specimen surfaces and apply uniform load. Semi-articulated fixtures have some articulating or tilting capabilities and may be used with specimens that have flat and parallel surfaces, such as on as-machined specimens. A semi-articulating fixture has pairs of upper and lower bearings that articulate to match the specimen surfaces, as shown in Figures B.2 and B.3. Fully articulated fixtures have more moving parts and are necessary for specimens that do not have flat and parallel surfaces. They allow independent articulation of the bearings. Fully articulated fixtures often are necessary for as-fired, heat-treated or oxidized specimens, since uneven loading can cause twisting and severe errors. A fully articulating fixture may also be used with machined specimens.

5.2.2 Bearings

Specimens shall be loaded and supported by bearings. The bearings may be cylindrical rollers or cylindrical bearings. The bearings shall be made of a steel which has a hardness of no less than HRC 40 for specimen strengths up to 1 400 MPa, or no less than HRC 46 for specimen strengths up to 2 000 MPa. Alternatively, the bearing may be made of a ceramic or hardmetal with an elastic modulus between 200 GPa and 500 GPa and

a flexural strength greater than 275 MPa. The bearing length shall be greater than or equal to 12 mm. The bearing diameter shall be approximately 1,5 times the specimen thickness (d). Diameters between 4,5 mm and 5 mm are recommended. The bearings shall have a smooth surface and shall have a diameter that is uniform to $\pm 0,015$ mm. The bearings shall be free to roll in order to eliminate friction. In four-point flexure, the two inner bearings shall be free to roll inwards, and the two outer bearings shall be free to roll outwards. In three-point flexure, the two outer bearings shall be free to roll outwards, and the inner (middle) bearing shall not roll.

NOTE 1 Friction can cause errors in the stress calculations. The rolling can be accomplished by several designs. The bearing can be mounted in roller bearing or cylindrical bearing assemblies. It is also acceptable, and simpler, for the bearings to be free to roll on the fixture surface, as shown in Figure 2.

The bearing diameter is specified on the basis of competing requirements. The bearings should not be so large as to cause excessive change in the moment arm as a specimen deflects, as this can create errors from contact-point tangency shift. On the other hand, the bearings should not be so small as to create excessive wedging stresses in the specimen or create contact stresses that damage the fixture.

NOTE 2 The bearing hardness and stiffness requirements and guidelines are intended to ensure that specimens with strengths up to 1 400 MPa (or 2 000 MPa), and elastic moduli as high as 500 GPa, can be tested without damaging the fixture. Higher-strength or stiffer ceramic specimens can require harder bearings. For example, if the bearing elastic modulus is greater than 500 GPa, then it is advisable to lengthen the bearings and the fixture support width to more than 12 mm to distribute the forces over a longer bearing length.

5.2.3 Four-point fixture: semi-articulating

Figure B.2 a) shows the actions of the bearings in this fixture. The two inner bearings shall be parallel to each other to within 0,015 mm over their length (≥ 12 mm in accordance with 5.2.2). The two outer bearings shall be parallel to each other to within 0,015 mm over their length. Either the two inner or the two outer bearings shall be capable of articulating (tilting) together as a pair to match the specimen surface. All four bearings shall rest uniformly and evenly across the specimen surface. The fixture shall apply equal load to all four bearings. All four bearings shall be free to roll.

5.2.4 Four-point fixture: fully articulating

Figure B.2 b) shows the actions of the bearings in this fixture. One bearing need not articulate (tilt). The other three bearings shall articulate (tilt) independently to follow the specimen surface. All four bearings shall rest uniformly and evenly across the specimen surface. The fixture shall apply equal load to all four bearings. All four bearings shall be free to roll.

5.2.5 Three-point fixture: semi-articulating

Figure B.3 a) shows the actions of the bearings in this fixture. The two outer bearings shall be parallel to each other to within 0,015 mm over their length (≥ 12 mm in accordance with 5.2.2). The two outer bearings shall articulate together to follow the specimen surface, or the middle bearing shall articulate to follow the specimen surface. All three bearings shall rest uniformly and evenly across the specimen surface. The fixture shall be designed to apply equal load to the two outer bearings. The two support (outer) bearings shall be free to roll outwards. The middle bearing shall be fixed and not free to roll.

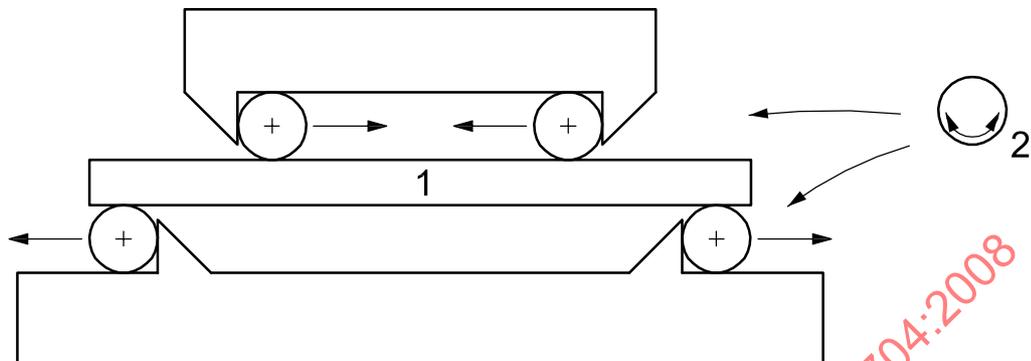
5.2.6 Three-point fixture: fully articulating

Figure B.3 b) and c) show the actions of the bearings in this fixture. Any two of the bearings shall be capable of articulating (tilting) independently to rest uniformly and evenly across the specimen surface. The fixture shall be designed to apply equal load to the two outer bearings. The two support (outer) bearings shall be free to roll outwards. The middle bearing shall not roll.

5.2.7 Positioning of bearings

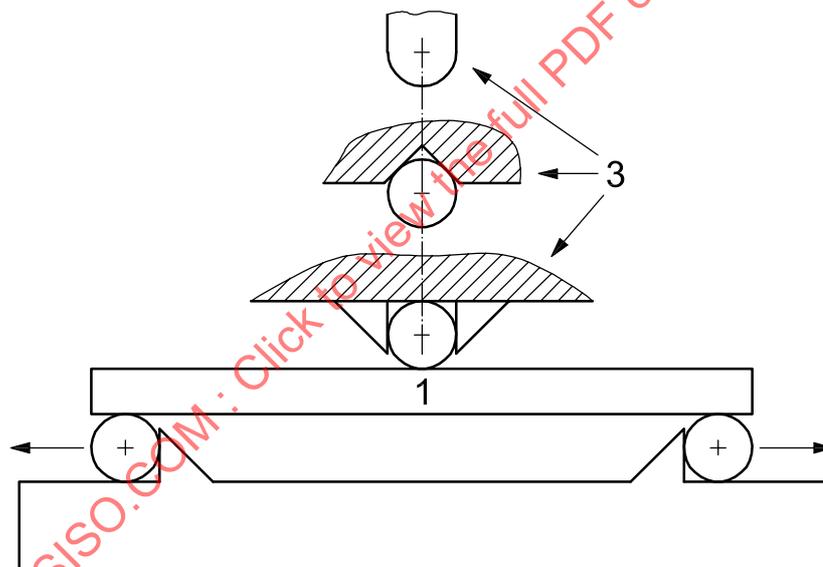
The bearings shall be positioned so that the spans are accurate to within $\pm 0,1$ mm. The middle bearing for the three-point fixture shall be positioned midway between the outer bearings to within $\pm 0,1$ mm. The inner bearings for the four-point fixture shall be centred over the outer bearings to within $\pm 0,1$ mm.

NOTE The positions of the bearings can be defined either by the use of captive bearings, or by appropriate stops against which the bearings are held at the commencement of a test. The spans can be measured to the nearest 0,1 mm using a traveling microscope or other suitable device. The spans can also be verified by measurement of the distances between bearing stops and adding (outer span) or subtracting (inner span) the radii of the bearing cylinders.



The four bearings shall be free to roll.

a) Four-point flexure



The two outer bearings are free to roll outwards, but the middle bearing shall be non-rolling.

b) Three-point flexure

Key

- 1 specimen
- 2 alternative rolling bearings
- 3 alternative loading bearing arrangements

Figure 2 — Schematic representation of fixtures showing the rolling action of the bearing

5.2.8 Fixture material

The fixture which supports and aligns the bearings shall be sufficiently hard, so that the bearings do not permanently deform the fixture.

NOTE Line-contact loadings can deform the fixture. The hardness of the fixture will depend upon the design of the fixture. If the bearings are at least 12 mm wide and the fixture is 12 mm wide or more, then a fixture made of steel with an HRC of 25 or greater will be adequate.

5.3 Micrometer

A micrometer, such as that described in ISO 3611 but with a resolution of 0,002 mm, shall be used to measure the specimen dimensions. The micrometer shall have flat anvil faces such as those shown in ISO 3611. The micrometer shall not have a ball tip or sharp tip since these might damage the specimen. Alternative dimension-measuring instruments may be used, provided that they have a resolution of 0,002 mm or finer.

6 Test specimens

6.1 Specimen size

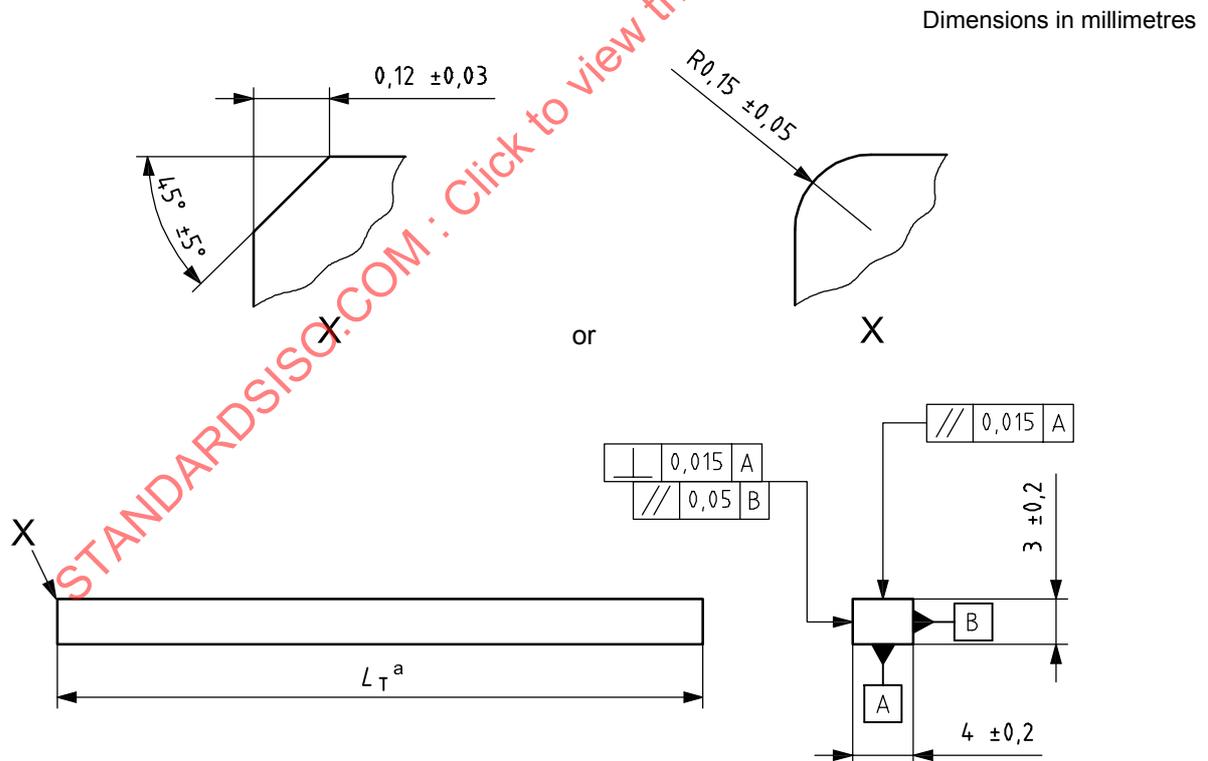
6.1.1 Machined specimens

Specimen dimensions are shown in Figure 3. Cross-sectional tolerances shall be $\pm 0,2$ mm. The parallelism tolerance on opposite longitudinal faces is 0,015 mm.

NOTE The terms “specimen” and “test piece” are used interchangeably in this International Standard.

6.1.2 As-fired or heat-treated specimens

Specimen dimensions may be altered, as required, but deviations from the specifications in 6.1.1 and Figure 3 shall be stated in the test report.



^a $L_T \geq 35$ mm for 30 mm test fixtures.

$L_T \geq 45$ mm for 40 mm test fixtures.

Figure 3 — Standard test specimen

6.2 Specimen preparation

6.2.1 General

This International Standard allows several options for specimen preparation. In all cases, the end faces of the specimen do not need special preparation or finishing. A minimum of two long edges on one 4 mm wide face shall be chamfered or rounded, as shown in Figure 3. It is highly recommended that all four long edges be chamfered or rounded. Although a surface finish specification is not part of this International Standard, it is highly recommended that the surface roughness be measured and reported.

NOTE Surface preparation of test specimens can introduce machining flaws (especially microcracks beneath the specimen surface) which can have a pronounced effect on flexural strength. Machining damage can either be a random interfering factor, or an inherent part of the strength characteristics to be measured. Surface preparation can also create residual stresses. Final machining steps (including polishing) can or cannot negate machining damage introduced from prior, coarser machining steps.

6.2.2 As-fired

The flexure specimen is fabricated by sintering or some other process, such that no machining is required. In this case, the purpose is to measure the strength of the specimen with an as-fired surface. An edge chamfer or rounding is recommended and can be made before sintering.

As-fired specimens are especially prone to twist or warpage. They may not meet the parallelism requirements given in 6.1.1, in which case a fully articulating fixture should be used in testing.

One surface of an as-fired part may be machined to help minimize twisting or warpage effects. The machined surface should be placed in contact with the inner bearings (specimen compression side) during testing.

6.2.3 Customary machining procedure

In instances where a customary machining procedure has been developed that is completely satisfactory for a class of materials (i.e. it introduces minimal or no unwanted surface damage or residual stress), then this customary procedure is permitted. The test report shall include details of the procedure, especially the wheel grits, wheel bonding (resin, metal, vitreous glass, other) and the material removed per pass. The long edges of the specimen shall be rounded or chamfered, as shown in Figure 3.

6.2.4 Component-matched procedure

The specimen shall have the same surface preparation as that given to a component. The test report shall include details of the procedure, especially the wheel bonding (resin, metal, vitreous, other) and the material removed per pass. The long edges of the specimen shall be rounded or chamfered, as shown in Figure 3.

6.2.5 Basic machining procedure

If the procedures in 6.2.2 to 6.2.4 are not applicable, then the following procedure may be used.

NOTE The procedure specified below is a general-duty, conservative practice. It is intended to minimize machining damage or residual stresses in a broad range of ceramics. Faster or more aggressive removal rates can be suitable for some materials. Alternatively, some very brittle ceramics can require a more conservative preparation.

6.2.5.1 Specimens shall be ground in the longitudinal direction, as shown in Figure 4.

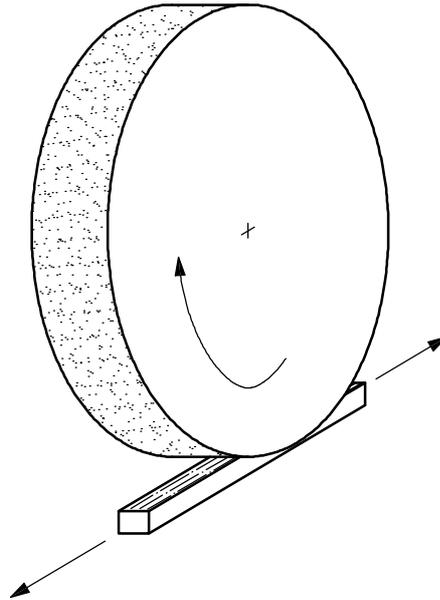


Figure 4 — Surface grinding parallel to the specimen longitudinal axis

6.2.5.2 All grinding shall be done with an ample supply of filtered coolant, in order to keep the work piece and wheel flooded and particles flushed. Grinding shall be in at least two stages, ranging from coarse to fine rates of material removal.

6.2.5.3 Coarse grinding shall be carried out using a diamond wheel rounded to within 0,03 mm and of grit size not exceeding 120 mesh (D 126), using a depth of cut not exceeding 0,03 mm per pass. Alternatively, a creep-feed grinding process may be used for the coarse grinding step.

6.2.5.4 Finishing machining shall be carried out using a diamond wheel of grit size between 320 mesh and 800 mesh (e.g. D 46 or finer), using a depth of cut not exceeding 0,002 mm per pass. Final finishing shall remove no less than 0,06 mm of material per face. Approximately equal stock shall be removed from opposite faces.

6.2.5.5 The long edges shall be uniformly chamfered at 45° to a size of 0,12 mm ± 0,03 mm, as shown in Figure 3. Alternatively, they can be rounded to a radius of 0,15 mm ± 0,05 mm. Edge chamfering or rounding shall be comparable to that applied to the specimen surfaces in the fine-finishing step. The direction of machining shall be parallel to the specimen's long axis.

If, for some reason, the chamfers are larger than the specified size range (e.g. for the removal of very large chips), then the stresses should be corrected for the reduced second moment of inertia of the specimen cross-section. Annex D may be consulted for this correction.

6.2.5.6 The final dimensions of the specimen shall be in accordance with 6.1.1 and Figure 3.

6.2.6 Parallelism, orthogonality and chamfer sizes

Ensure that the parallelism, orthogonality and chamfer sizes of the test-pieces are checked. If the test pieces have been prepared by an established procedure with a demonstrated reliability, then inspect only a few (3 to 5 per batch) test pieces to verify conformance. The basis for acceptance/rejection of parallelism shall be by measurements made across the thickness and across the width at each end of the intended support span and in the centre. A flat-faced hand micrometer, dial indicator/comparator stand or digital indicator stand may be used. The acceptability for orthogonality shall be based on the use of an engineering shadowgraph, optical comparator or optical microscope. The basis for chamfers shall be based on microscope examination and measurement.

6.2.7 Handling of specimens

The specimens shall be handled with care, in order to avoid the introduction of damage after specimen preparation. Specimens shall be stored separately and not allowed to impact or scratch each other.

6.2.8 Number of specimens

A minimum of 10 specimens shall be required for the purpose of estimating the mean flexural strength. A minimum of 30 specimens shall be used if a statistical strength analysis (for example, a Weibull analysis) is to be made.

NOTE The use of 30 specimens will help obtain good confidence limits for the strength distribution parameters such as a Weibull modulus. Thirty specimens will also help detect multiple flaw populations if they exist.

7 Procedure

7.1 Measure the specimen width, b , and thickness, d , with a resolution of 0,002 mm. The specimen size may be measured either before or after the test. If the specimen is measured before the test or if there is excessive fragmentation, measure the specimen dimensions as close to the midpoint (along the specimen length) as possible; otherwise, measure the specimen dimensions at or near the fracture location after the test. Care shall be taken to not introduce surface damage when using the micrometer.

7.2 Test the specimens on the appropriate fixture in either the three- or four-point configuration. The four-point configuration is preferred. A fully articulating fixture shall be used if the specimen parallelism requirements cannot be met.

7.3 Ensure that the test fixtures are clean and free of any fracture debris from previous tests, that the bearings are free of burrs or deep scratches and that the bearings are free to roll and articulate.

7.4 Place each specimen in the test fixture with a 4 mm wide face resting on the bearings. If the specimen has only two edges chamfered or rounded, place the specimen so that these chamfers are on the tension side. Avoid damaging the specimen. Align the specimen carefully. The specimen should have an approximately equal amount of overhang beyond the two outer bearings. Centre the specimen carefully within 0,1 mm of the axis of load application (front to back), as illustrated in Figure 5. Positioning stops for the specimen are strongly recommended.

This is especially important with fully articulating fixtures which may cause the specimen to shift during articulation. The fixture design should not allow excessive shifts.

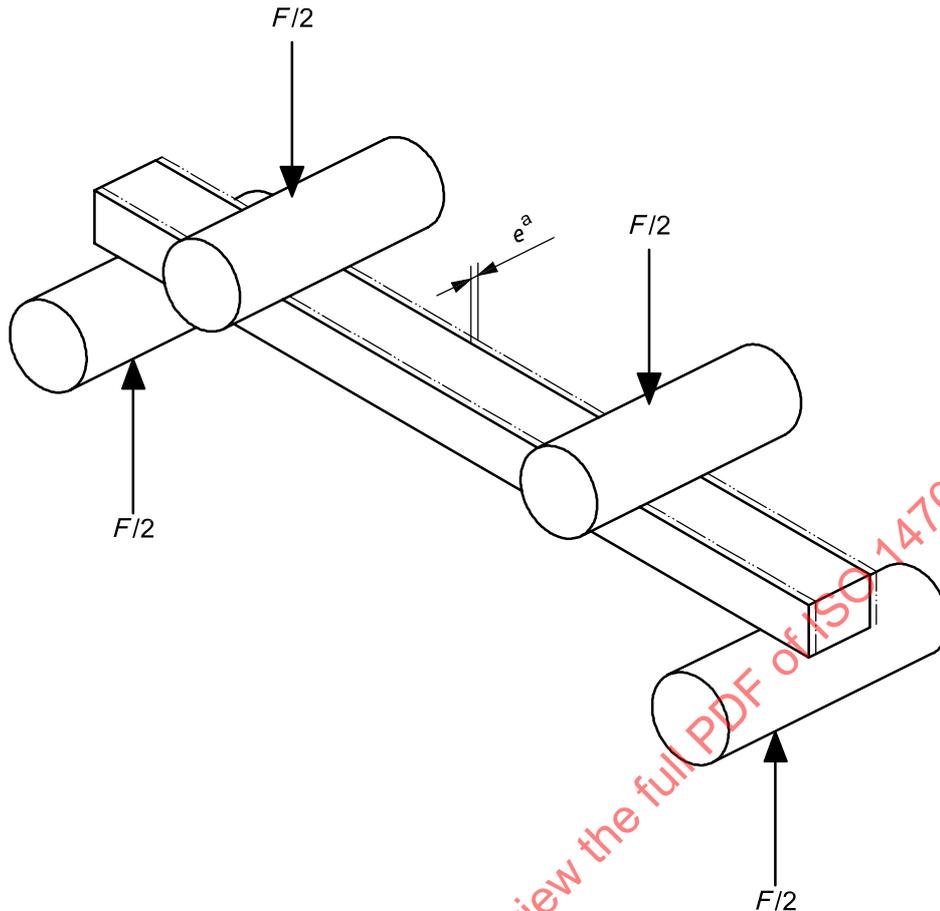
7.5 Apply to the specimen a slight preload of no more than 10 % of the mean strength. If possible, inspect the lines of contact of all the bearings and the specimen, to ensure that there is an even line loading. If the loading is not even, then unload the specimen and adjust the fixtures as required to obtain even loading. Inspect the bearings to ensure that they are in their correct starting positions.

7.6 Gently mark the specimen to identify the approximate locations of the two inner loading bearings (four point) or the middle bearing (three point). Also mark the specimen so that the compression surface can be distinguished from the tensile surface. Carefully drawn pencil or felt-tip pen marks are suitable.

7.7 Place cotton, tissue, foam or another material around or near the specimen, to prevent the specimen fragments from flying around the fixture after fracture. These materials shall not interfere with the load application or inhibit fixture articulation or bearing rolling motions.

NOTE This will prevent unnecessary secondary fractures, and will help preserve the primary fracture pieces for subsequent fractographic analysis.

7.8 For safety reasons, place a protective screen around the test fixture to trap the fracture fragments.



^a $e < 0,1 \text{ mm}$

Figure 5 — Alignment of the specimen under the axis of load application

7.9 The testing machine cross-head rate shall be 0,5 mm/min, provided that the time to fracture is within 3 s to 30 s.

NOTE This crosshead rate will strain the specimen at a rate of approximately $1 \times 10^{-4} \text{ s}^{-1}$.

7.10 The crosshead rate specified in 7.9 should result in a time to failure from 3 s to 30 s. This assumes that the test fixtures are rigid and most of the machine crosshead travel is applied to the specimen. If the time to failure of a specimen is outside this range, then faster or slower crosshead rates should be used, so that the time to failure is within 3 s to 30 s.

7.11 The effects of time-dependent phenomena, such as stress or slow crack growth corrosion (from water vapour in laboratory ambient air) on the measured flexural strength can be important for some sensitive materials, even for the relatively short times in the test. To eliminate or minimize the environmental sensitivity, surround the test jig with an environmental chamber or envelope (for example, a clear polyethylene bag) and flush with dry nitrogen or argon from a gas cylinder before the test. Run the test with inflowing dry nitrogen or argon gas. Alternatively, coat the tensile face of the specimens with paraffin oil (preferably heat treated at approximately 170 °C for 1 h to 2 h) or silicon oil, and then test the specimen in laboratory ambient conditions. The paraffin oil may interfere with subsequent fractographic analysis, however. Alternatively, the tests may be done in a vacuum ($\sim 10^{-3} \text{ Pa}$ or less).

7.12 Apply the test force at the specified rate and record the peak load at fracture. Measure the peak load with an accuracy of $\pm 1 \%$ or better.

7.13 Retrieve the fracture fragments for later examination.

Only a few pieces need be saved. Tiny fragments or tiny shards are often inconsequential since they do not contain the fracture origin. With experience, it is usually not difficult to determine which pieces are important and should be retained. Annex C may be consulted for further guidance. It is recommended that the specimen be retrieved with tweezers after fracture, or the operator may wear gloves, in order to avoid contamination of the fracture surfaces for possible fractographic analysis.

7.14 Observe the approximate fracture-initiation location with the primary purpose of observing if fractures occurred within the inner span in four-point flexure. Fracture of specimens may occasionally occur outside the inner span or at an inner loading bearing. These specimens shall be included in the data set. See Annex C for more guidance on the interpretation of fracture patterns in flexural specimens.

NOTE 1 This is a normal consequence of the scatter in fracture-origin sizes and locations. Fractures from origins outside the inner span are more likely to occur with materials with high strength scatter, i.e. a low Weibull modulus.

If many specimens fracture outside the inner span, or if many fractures begin directly under the inner loading bearings in four-point flexure, there may be a fixture misalignment. Testing shall be stopped until the problem is remedied.

NOTE 2 Multiple fractures are common in high-strength ceramics. In many instances, a secondary fracture will occur directly under an inner bearing. This is common and the strength result is probably completely satisfactory. Guidance on the interpretation of fracture origins and patterns is included in Annex C.

7.15 Measure and record the relative humidity and ambient temperature during the test sequence.

8 Calculation

8.1 The standard formula for the flexural strength in four-point flexure is:

$$\sigma_f = \frac{3Fa}{bd^2} \quad (1)$$

where

σ_f is the flexural strength, in megapascals;

F is the fracture load, in newtons;

a is the length of the fixture moment arm (10 mm);

b is the specimen width, in millimetres;

d is the specimen thickness, parallel to the direction of test force, in millimetres.

NOTE 1 a is 10 mm for both fixtures specified by this standard; $a = L/4$ for 1/4-point, four-point flexure, and $a = L/3$ for 1/3-point, four-point flexure. (See Figure 1.)

NOTE 2 Equation 1 gives the nominal flexural strength of a specimen. See the last paragraph of 8.2.

8.2 The standard formula for the flexural strength in three-point flexure is:

$$\sigma_f = \frac{3FL}{2bd^2} \quad (2)$$

where

- σ_f is the flexural strength, in megapascals;
- F is the fracture load, in newtons;
- L is the length of the fixture outer span, in millimetres;
- b is the specimen width, in millimetres;
- d is the specimen thickness, parallel to the direction of test force, in millimetres.

NOTE The three-point fixture outer span is either 40 mm or 30 mm, as specified in this International Standard.

Equations 1 and 2 are the customary and correct formulae for reporting the nominal flexural strength of a specimen. They give the maximum stress occurring in the specimen at the instant of fracture. The equations do not necessarily give the stress that was acting directly upon the flaw that caused fracture. In some instances, e.g. fracture mirror or fracture toughness calculations, the fracture stress should be corrected for subsurface origins, breaks outside the inner span in four-point flexure, or fractures not directly beneath the middle bearing in three-point flexure.

8.3 If the chamfer sizes are larger than those specified in 6.2.6 and Figure 3, then the flexural strengths should be corrected, as described in Annex D.

8.4 The mean strength, $\bar{\sigma}_f$, and the standard deviation, s , are given by:

$$\bar{\sigma}_f = \frac{\sum_{i=1}^n \sigma_{f,i}}{n} \tag{3}$$

$$s = \left[\frac{\sum_{i=1}^n (\sigma_{f,i} - \bar{\sigma}_f)^2}{n-1} \right]^{1/2} \tag{4}$$

where

- $\sigma_{f,i}$ is the strength of the i th specimen;
- n is the total number of specimens.

9 Test report

The test report shall include the following information:

- a) a reference to this International Standard, i.e. ISO 14704:2008;
- b) the test configuration (four- or three-point flexure), the fixture size, a statement on whether the fixture was semi-articulating or fully articulating, and a statement that confirms that the bearings were free to roll;
- c) the number of specimens (n) tested;

- d) all relevant material data, including vintage, billet or component identification number (the date the material was manufactured should be reported, if available);
- e) specimen preparation procedures, including all details of machining preparation;
- f) heat treatments or exposures, if any;
- g) flexural test environment, including humidity and temperature;
- h) crosshead rate, in mm/min, and the approximate average time to fracture, in seconds;
- i) for each specimen tested, $\sigma_{f,i}$, the flexural strength to three significant figures (e.g. 537 MPa);
- j) the mean strength, σ_f , and the standard deviation, s . The following notation shall be used to report the mean strengths:
 - 1) $\sigma_{(N,L)}$ to denote strengths measured in ($N = 4$ or 3)-point flexure, and ($L = 40$ mm or 30 mm) fixture outer-span size.

EXAMPLES

- $\sigma_{(4,40)} = 537$ MPa denotes a mean flexural strength of 537 MPa when measured in four-point flexure with 40 mm span fixtures.
- $\sigma_{(3,30)} = 580$ MPa denotes a mean flexural strength of 580 MPa when measured in three-point flexure with 30 mm span fixtures.

It is also recommended that the relative humidity of test environment be reported as follows:

- 2) $\sigma_{(N,L)} = \text{XXX}$ [relative humidity (RH) % or environment] to denote strengths measured in an atmosphere with RH % or other environmental conditions.

EXAMPLES

- $\sigma_{(4,40)} = 537$ MPa (45 %) denotes a mean flexural strength of 537 MPa, when measured in four-point flexure with 40 mm span fixtures in laboratory ambient conditions at 45 % relative humidity;
- $\sigma_{(3,30)} = 580$ MPa (dry N₂) denotes a mean flexural strength of 580 MPa, when measured in three-point flexure with 30 mm span fixtures in a dry-nitrogen-gas environment;
- $\sigma_{(3,30)} = 580$ MPa (paraffin oil coated) denotes a mean flexural strength of 580 MPa, when measured in three-point flexure with 30 mm span fixtures with paraffin-oil-coated specimens;

- k) a statement reporting whether the chamfers are within specifications; if they are not, then include a statement whether flexural strength has been corrected for the chamfer size;
- l) any deviation(s) from the procedures described in this test method, and the reason for the deviation(s);
- m) name of testing laboratory, date of test, name of person conducting the tests, name of testing machine.

10 Strength scaling factors

The different test pieces and fixture sizes permitted by this International Standard may produce different mean strengths. Annex E includes Weibull strength scaling factors which may facilitate comparison of results.

Annex A (informative)

General information

The flexural strength of a ceramic depends on the inherent resistance to fracture and the presence of fracture origins in the ceramic; variations in these cause a natural scatter in test results for a sample of test specimens. Fractographic analysis of fracture surfaces, although beyond the scope of this International Standard, is highly recommended for all purposes, especially if the data will be used for design.

Flexural strength may also be influenced by many parameters associated with the test procedure. These include the loading rate, test environment, specimen size, test fixture details and specimen preparation. Surface preparation is especially important, since the maximum stress at fracture is on the specimen surface. With proper care and good machining practice, it is possible to obtain fractures from the material's natural flaws; otherwise, the test may only measure machining damage. This International Standard allows several options for the machining of specimens, and includes a general procedure ("Basic" machining procedure, see 6.2.5) which is satisfactory for many (but certainly not all) ceramics. The general procedure uses progressively finer longitudinal grinding steps that are designed to minimize subsurface microcracking. Longitudinal grinding aligns the most severe microcracks parallel to the specimen tension-stress axis. This allows a greater opportunity of measuring the "potential strength" of the material, as controlled by the material's natural flaws. In contrast, transverse grinding aligns the severest machining microcracks perpendicular to the tension-stress axis and the specimen is more likely to fracture from the machining microcracks. Transverse-ground specimens in many instances may provide a more "practical strength" which is relevant to machined ceramic components, whereby it may not be possible to favourably align the machining direction.

The specifications given in this International Standard were chosen to provide a balance between controlling experimental error, maintaining practicality and efficiency of testing. If the procedures in this International Standard are followed, it is estimated that the error in flexural strength for one specimen is less than 2 %.

Two fixtures and corresponding specimen sizes have been adopted in this International Standard. The larger fixtures (20 mm × 40 mm) had previously been standardized in the United States and Europe. The shorter fixtures (10 mm × 30 mm) had previously been standardized in Japan, Korea and the People's Republic of China. The larger fixture-specimen set will expose more material to the full stress and, in general, produce a slightly lower strength than the shorter fixture-specimen set. This is normal for ceramics wherein fracture origins of different size or severity are distributed through the volume or surface. Weibull statistics often can correlate the strengths quite efficiently; e.g. for a material with a single volume-distributed fracture-origin type and a Weibull modulus of 10, the larger four-point specimen should have a strength 6 % lower than the strength for the smaller specimen.

The three-point test configuration exposes only a very small portion of the specimen to the maximum stress. Therefore, strengths are likely to be much higher than four-point flexural strength. Three-point flexure has some advantages. It uses simpler test fixtures, it is easier to adapt to high temperature and fracture toughness testing, and it is sometimes helpful in Weibull statistical studies. Four-point flexure is preferred and recommended for most characterization work.

For additional information on flexural testing in general and for design, consult [1] in the Bibliography. For additional information on experimental errors in flexural testing of ceramics including correction factors for oversized chamfers, consult [2] in the Bibliography.

Annex B (normative)

Test fixtures

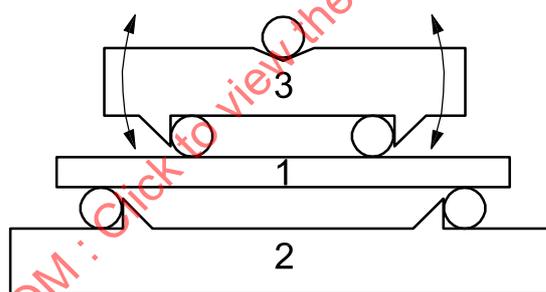
The fixtures must articulate (tilt) to ensure even loading from side to side, as shown in Figure B.1. Additional articulation is necessary, as described below, to ensure that the bearings make even contact on the specimen top and bottom surfaces.

Semi-articulating fixtures are designed to apply uniform and even loading to test specimens that have flat and parallel surfaces. The top or bottom pair of bearings shall articulate to match the specimen surface, as shown in Figures B.2 a) and B.3 a).

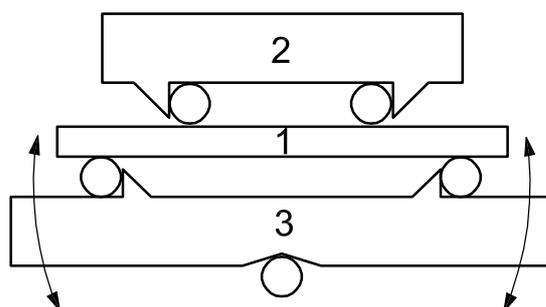
Fully articulating fixtures shall be used for specimens that do not meet the specimen parallelism requirements of 6.1.1 and Figure 3. The bearings articulate independently to match the specimen surface, as shown in Figures B.2 b) and B.3 b). Fully articulating fixtures may also be used with flat and parallel specimens.

Figures B.1, B.2 and B.3 illustrate fully and semi-articulating fixture actions. Figures B.4 and B.5 show some examples of designs. Other designs may be acceptable.

All fixtures shall have bearings that are free to roll, with the exception that the middle bearing in three-point flexure shall be non-rolling.



a) Upper pair of bearings which articulate

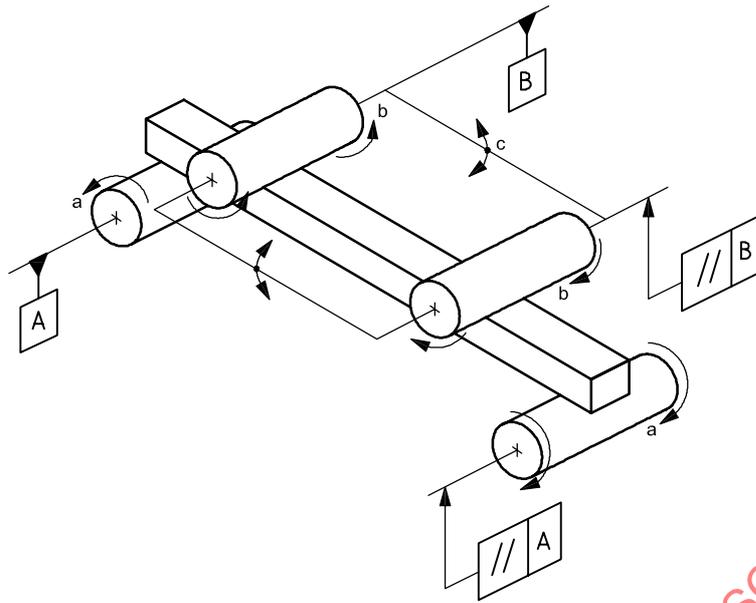


b) Lower pair of bearings which articulate

Key

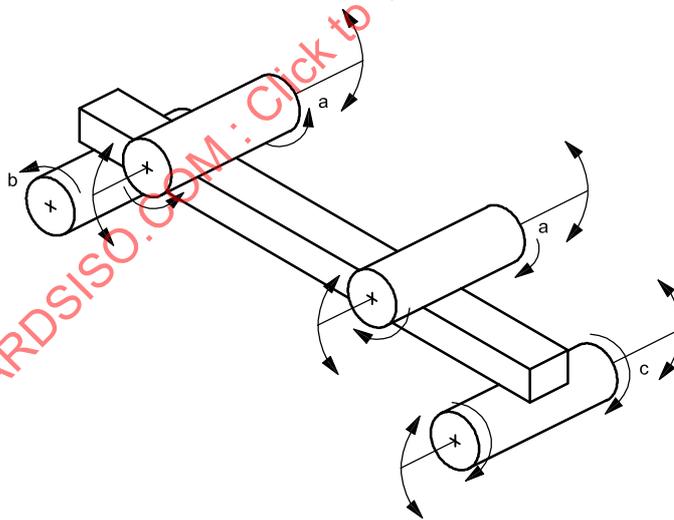
- 1 specimen
- 2 fixed
- 3 articulating

Figure B.1 — Four-point flexure fixture with top or bottom articulation to ensure even loading from side to side (both arrangements are acceptable)



- a The outer bearings are parallel and free to roll outwards.
- b The inner bearings are parallel and free to roll inwards.
- c The inner bearings articulate together as a pair to follow the specimen top surface. (Alternatively, the two bottom bearings can articulate to follow the bottom surface.)

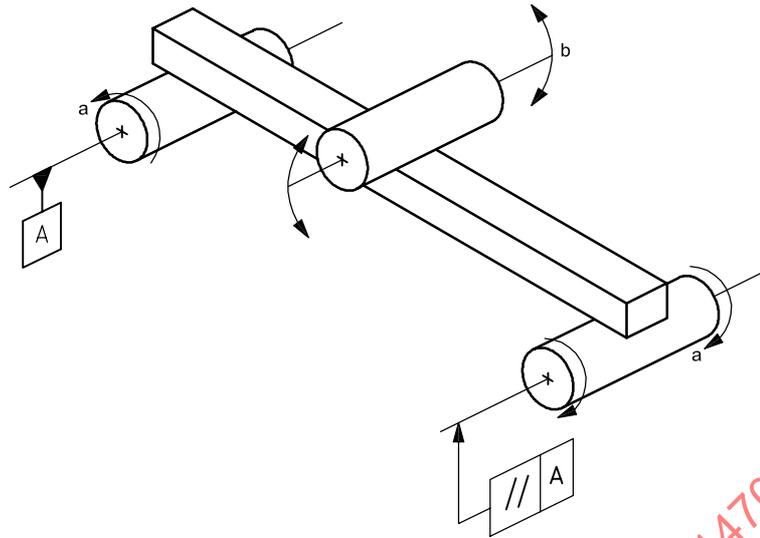
a) Semi-articulating



- a The inner bearings articulate and are free to roll inwards, and they can articulate independently to follow the specimen top surface.
- b Not articulating (fixed) but free to roll.
- c Articulating and free to roll outwards.

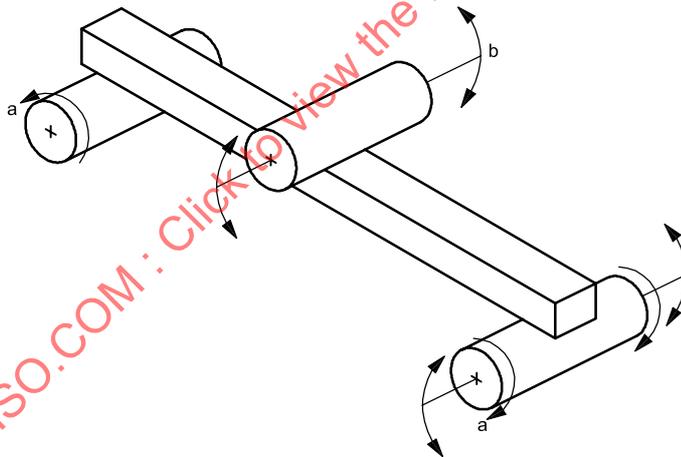
b) Fully articulating

Figure B.2 — Four-point flexure fixture



- a The two support bearings are parallel to each other and free to roll outwards.
- b The middle bearing does not roll, but it can articulate to follow the specimen top surface.

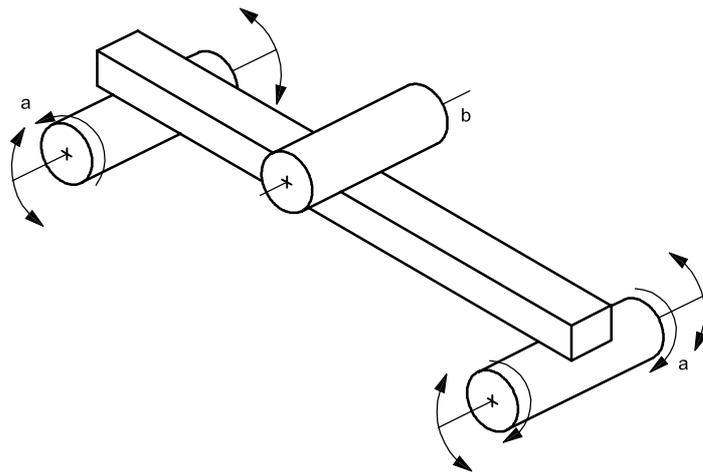
a) Semi-articulating



- a The two support bearings are free to roll outwards.
- b The middle bearing does not roll, but it can articulate to follow the specimen top surface. Support bearings can articulate to follow the specimen surface.

b) Fully articulating

Figure B.3 (continued)

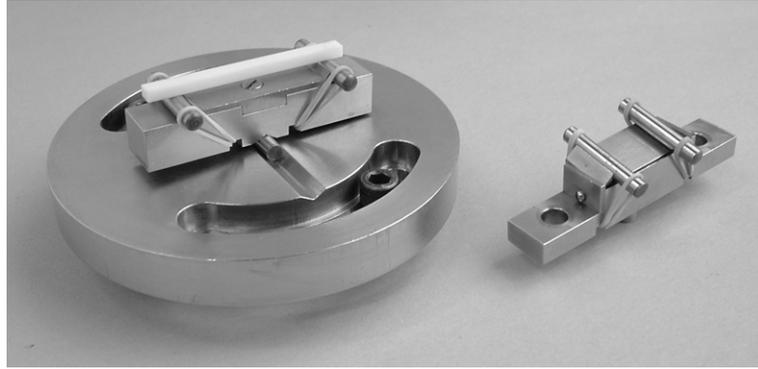


- a The two support bearings are free to roll outwards, and they can articulate to follow the specimen surface.
- b The middle bearing does not roll and does not articulate.

c) Fully articulating (alternative design)

Figure B.3 — Three-point flexure fixture

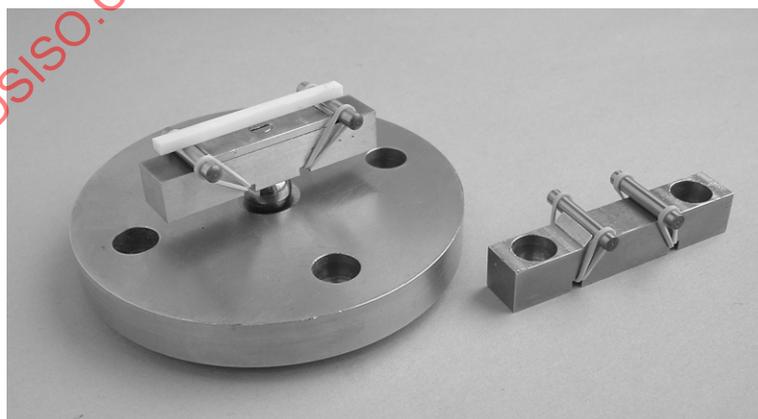
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- a) The inner pair of bearing rollers (on the right) are parallel and articulate together as a pair in a cradle assembly. The bottom outer bearing rollers (on the left) are parallel. Left-to-right articulation is carried out by a pivot underneath the bottom base. This shows a 20 mm × 40 mm span combination.

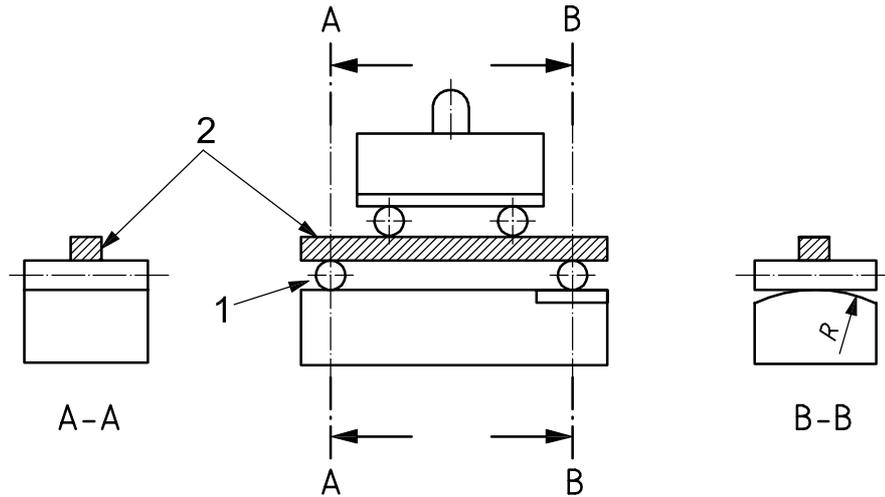


- b) The same fixture as shown in a), but with inserts on the right to convert the inner span to 10 mm and a new insert on the bottom piece on the left to convert the outer span to 30 mm. The two small pieces on the bottom left are attached to the back of the fixture to hold the specimen in the correct front-to-back position. They may be used with either 20 mm × 40 mm or 10 mm × 30 mm configurations.



- c) Alternative design with a ball on the bottom for articulation. The bottom base pivots on the ball that gives left-to-right and front-to-back articulation. The outer span bearings (on the left) articulate as a pair such as that shown in Figure B.1b). The inner pair of rollers (on the right) are parallel and are fixed to the testing machine.

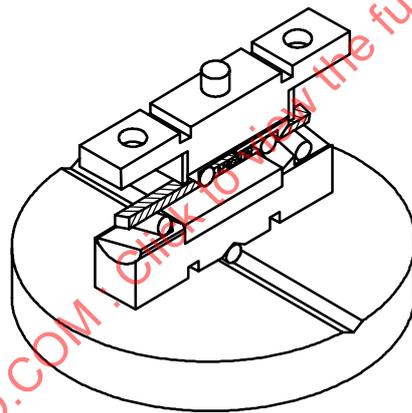
Figure B.4 — Examples of semi-articulated type fixtures



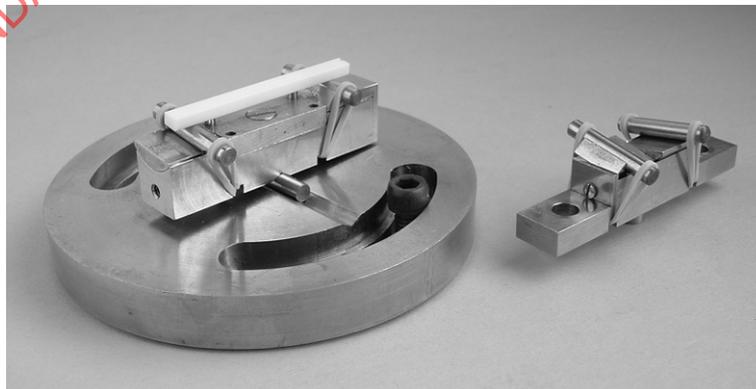
Key

- 1 bearing which does not articulate
- 2 specimen

a) **Schematic of a fixture with rounded base and top supports.** The bearing rollers may tilt or articulate to match the specimen surfaces. One of the four bearings (on the left) does not articulate. Shoulders or positioning stops for the bearing rollers are not shown for simplicity. Elastic bands, low-stiffness springs, or magnets may hold the bearing rollers in their correct initial positions.



b) **Schematic of a fixture with special cradles to hold the bearing rollers.** The cradles rotate about an axis that is on the specimen surface, so that the specimen does not shift when the cradles articulate or tilt.



c) Photograph of the fixture shown in b).

Figure B.5 — Examples of fully articulating fixtures

Annex C
(informative)

Typical fracture patterns in ceramic test specimens

Low-strength ceramics, which have a low energy level at fracture, typically break into only two pieces. Medium- to high-strength ceramics break into more pieces. Fractographic analysis can assist in determining the primary fracture origin. References [3] or [4] in the Bibliography may be consulted for further guidance.

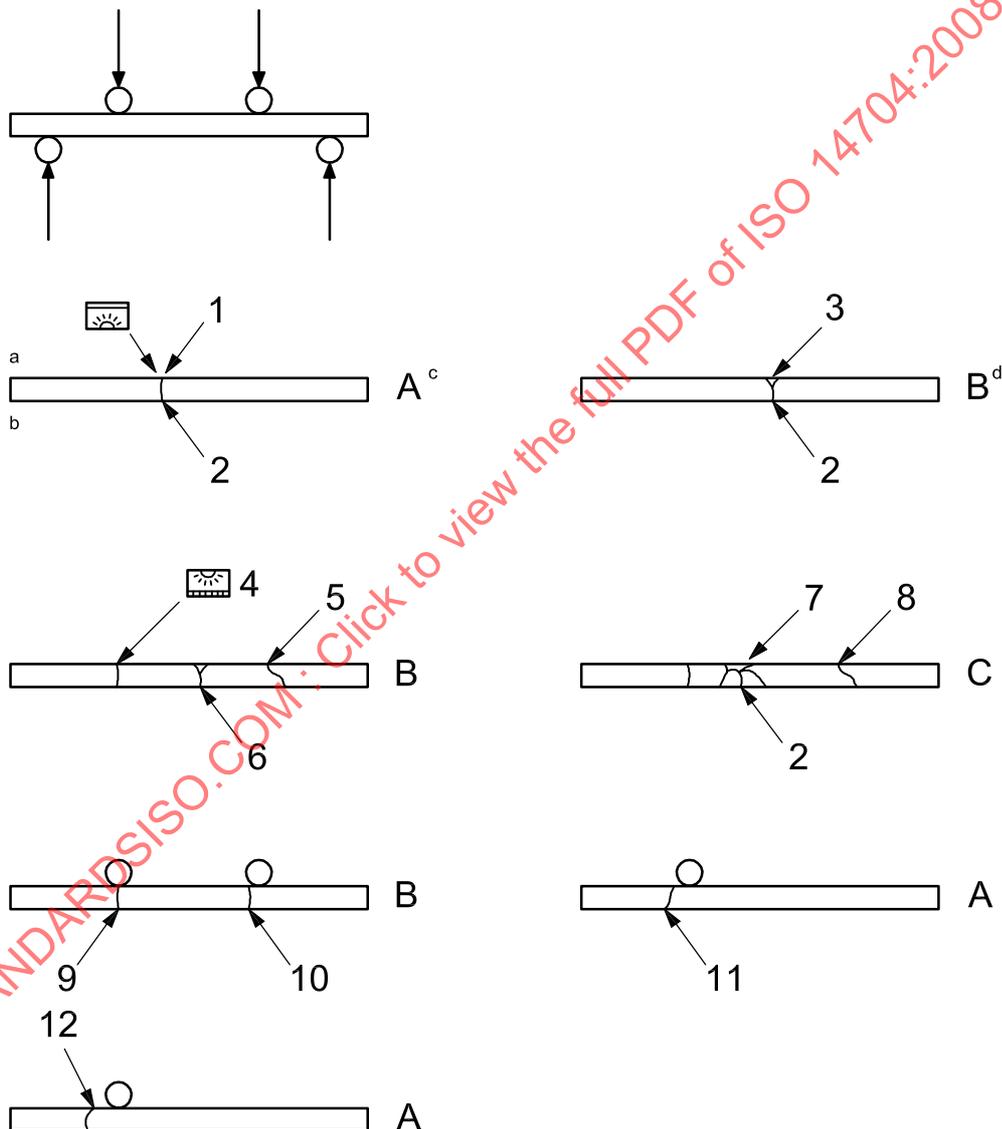


Figure C.1 (continued)

Key

- 1 compression curl
 - 2 origin — fracture surface is perpendicular to the tensile surface
 - 3 crack branch and double compression curl leading to a “Y” shaped pattern (upper fragment is not important and can be discarded)
 - 4 secondary fracture caused by the elastic release wave's reflection off the end faces (this often occurs at the loading bearings; note that the fracture mirror is on what was originally the compression side)
 - 5 secondary break — often at an angle
 - 6 primary fracture — origin
 - 7 crack branching and curving back to the tensile face
 - 8 secondary break
 - 9 secondary fracture at a loading bearing
 - 10 primary fracture — origin close to but not directly at a loading bearing
 - 11 break at or near a loading bearing (beware of misalignments or twisting errors and note the angle to the tensile surface)
 - 12 primary fracture outside the gauge length (legitimate due to severe flaw)
- A low-energy failure
 - B medium- to high-energy failure
 - C high-energy failure
- a Compression.
 - b Tension.
 - c Fracture surface is perpendicular to the tensile surface.
 - d Upper fragment is not important and can be discarded.

Figure C.1 — Typical fracture patterns in ceramic test specimen

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Annex D (informative)

Chamfer correction factors

Flexural strengths should be corrected for the presence of the corner chamfers if the chamfers are oversized. Chamfers or rounded edges cause an underestimate of the true maximum flexural strength.

The maximum stress in a flexure test piece is customarily calculated from simple beam theory, with the assumption that the test piece has a rectangular cross-section. The test piece chamfers reduce the second moment of inertia, I , of the test piece cross-section about the neutral axis. For a perfect rectangular cross-section, $I = (bd^3)/12$ where b is the width and d is the thickness. For a rectangular cross-section with four chamfered edges of size c , the adjusted moment of inertia from Reference [2] in the Bibliography is:

$$I = \frac{bd^3}{12} - \frac{c^2}{9} \left(c^2 + \frac{1}{2}(3d - 2c)^2 \right) \quad (\text{D.1})$$

where the second term on the right-hand side shows the reduction due to the chamfers. (A similar equation for rounded edges is available in Reference [2] in the Bibliography.)

If the chamfers or edge rounds are larger than those specified in Figure 3 ($c_{\max} = 0,15$ mm for chamfers or $R_{\max} = 0,20$ mm for rounded edges), then the flexural strengths should be corrected. The average chamfer size for a test piece may be used. The most accurate results may be obtained by measuring each test piece, but for many applications, an approximate chamfer size based on a sample of 5 test pieces may be adequate.

The correct flexural strength σ_f may be obtained by multiplying the apparent flexural strength, σ_f' , (calculated on the assumption that the cross-section is a simple rectangle) by a correction factor, Cor.

$$\sigma_f = \text{Cor} \sigma_f' \quad (\text{D.2})$$

Correction factors, Cor, for four chamfers or rounded edges are listed in Table D.1.

The chamfer geometry is shown in Figure D.1.

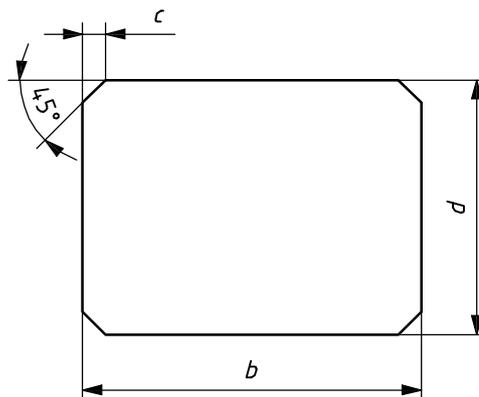


Figure D.1 — Chamfer geometry