Standard Specification for
Silicon Nitride Bearing Balls

This standard is issued under the fixed designation F2094/F2094M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification covers the establishment of the basic quality, physical/mechanical property, and test requirements for silicon nitride balls Classes I, II, and III to be used for ball bearings and specialty ball applications.

1.2 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

2. Referenced Documents

2.1 Order of Precedence:

2.1.1 In the event of a conflict between the test of this document and the references herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.2 ASTM Standards:

C1161 Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature
C1421 Test Methods for Determination of Fracture Toughness of Advanced Ceramics at Ambient Temperature

2.3 ANSI Standard:

ANSI/ASQC Z1.4 Sampling Procedures and Tables for Inspection by Attributes

2.4 ABMA Standards:

STD 10 Metal Balls

2.5 ASME Standard:

B 46.1 Surface Texture (Surface Roughness, Waviness, and Lay)

2.6 ISO Standards:

4505 Hardmetals—Metallographic Determination of Porosity and Uncombined Carbon

2.7 JIS Standards:

R 1601 Testing Method for Flexural Strength (Modulus of Rupture) of High Performance Ceramics
R 1607 Testing Method for Fracture Toughness of High Performance Ceramics

2.8 CEN Standards:

EN 843-1 Advanced Technical Ceramics—Monolithic Ceramics—Mechanical Properties at Room Temperature, Part 1. Determination of Flexural Strength
ENV 843-5 Advanced Technical Ceramics—Monolithic Ceramics—Mechanical Properties at Room Temperature, Part 5, Statistical Analysis

3. Terminology

3.1 Definitions of Terms Specific to This Standard:

3.1.1 ball diameter variation (Vdws)—ball diameter variation is the difference between the largest and smallest diameter measured on the same ball.

3.1.2 ball gage (S)—prescribed small amount by which the lot mean diameter should differ from nominal diameter, this amount being one of an established series of amounts. A ball gage, in combination with the ball grade and nominal ball diameter, should be considered as the most exact ball size specification to be used by a customer for ordering purposes.

3.1.3 ball gage deviation (ΔS)—difference between the lot mean diameter and the sum of the nominal diameter and the ball gage.

1 This specification is under the jurisdiction of ASTM Committee F34 on Rolling Element Bearings and is the direct responsibility of Subcommittee F34.01 on Rolling Element.


2 For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For Annual Book of ASTM Standards volume information, refer to the standard’s Document Summary page on the ASTM website.


4 Application for copies should be addressed to the American Bearing Manufacturer’s Association, 1200 19th Street NW, Suite 300, Washington, DC 20036-2401.

5 Application for copies should be addressed to the American Society of Mechanical Engineers (ASME), ASME International Headquarters, Three Park Ave., New York, NY 10016-5990, http://www.asme.org.

6 Application for copies should be addressed to the Japanese Standards Organization (JSA), 4-1-24 Akasaka Minato-Ku, Tokyo, 107-8440, Japan, http://www.jsa.or.jp.

3.1.4 **ball grade (G)**—specific combination of dimensional form and surface roughness tolerances. A ball grade is designated by a grade number followed by the letter “C” indicating Silicon Nitride Ceramic.

3.1.5 **blank lot**—single group of same-sized ball blanks processed together from one material lot through densification.

3.1.6 **deviation from spherical form** ($\Delta R_w$)—greatest radial distance in any radial plane between a sphere circumscribed around the ball surface and any point on the ball surface.

3.1.7 **finish lot**—single group of same-sized balls (which may be derived from multiple blank lots of the same material lot) processed together through finishing.

3.1.8 **lot diameter variation** ($V_{dw}$)—difference between the mean diameter of the largest ball and that of the smallest ball in the lot.

3.1.9 **lot mean diameter** ($D_{wml}$)—arithmetic mean of the mean diameter of the largest ball and that of the smallest ball in the lot.

3.1.10 **material lot**—single process lot of silicon nitride raw powder received from a material supplier.

3.1.11 **mean diameter of a ball** ($D_{wm}$)—arithmetic mean of the largest and the smallest actual single diameters of the ball.

3.1.12 **nominal diameter** ($D_w$)—size ordered that is the basis to which the nominal diameter tolerances apply. The nominal diameter is specified in inches or millimeters (decimal form).

3.1.13 **nominal diameter tolerance**—maximum allowable deviation from true specified nominal diameter for the indicated grade.

3.1.14 **single diameter of a ball** ($D_{ws}$)—the distance between two parallel planes tangent to the surface of the ball.

3.1.15 **surface roughness** ($Ra$)—surface irregularities with relative small spacings, which usually include irregularities resulting from the method of manufacture being used or other influences, or both.

3.1.16 **unit container**—container identified as containing balls from the same manufacture lot of the same composition, grade, and nominal diameter, and within the allowable diameter variation per unit container for the specified grade.

4. **Classification**

4.1 Silicon nitride materials for bearing and specialty ball applications are specified according to the following material classes (see Appendix X1 for typical current applications):

4.1.1 **Class I**—Highest grade of material in terms of properties and microstructure. Suitable for use in the most demanding applications. This group adds high reliability and durability for extreme performance requirements.

4.1.2 **Class II**—General class of material for most bearing and specialty ball applications. This group addresses the concerns of ball defects as is relative to fatigue life, levels of torque, and noise.

4.1.3 **Class III**—Lower grade of material for low duty applications only. This group of applications primarily takes advantage of silicon nitride material properties. For example:

Light weight, chemical inertness, lubricant life extension due to dissimilarity with race materials, etc.

5. **Ordering Information**

5.1 Acquisition documents should specify the following:

5.1.1 **Title, number, and date of this specification.**

5.1.2 **Class, grade, and size (see 4.1, 8.6, and 8.7).**

6. **Material**

6.1 Unless otherwise specified, physical and mechanical property requirements will apply to all material classes.

6.2 Silicon nitride balls should be produced from either silicon nitride powder having the compositional limits listed in Table 1 or from silicon metal powder, which after nitridation complies with the compositional limits listed in Table 1.

6.3 Composition is measured in weight percent. Testing shall be carried out by a facility qualified and approved by the supplier. Specific equipment, tests, and/or methods are subject to agreement between suppliers and their customers.

6.4 Compounds may be added to promote densification and enhance product performance and quality.

6.5 Iron oxides may be added to promote densification with the total iron content for the final product not to exceed 1.0 weight %.

6.6 Precautions should be taken to minimize contamination by foreign materials during all stages of processing up to and including densification.

6.7 A residual content of up to 2 % tungsten carbide from powder processing is allowable.

6.8 Final composition shall meet and be reported according to the specification of the individual supplier.

6.9 Notification will be made upon process changes.

6.10 Specific requirements such as specific material grade designation, physical/mechanical property requirements (for example, density) or quality or testing requirements shall be established by specific application. The special requirements shall be in addition to the general requirements established in this specification.

6.11 Typical mechanical properties will fall within the range listed in Table 2. Individual requirements may have tighter ranges. The vendor shall certify that the silicon nitride material supplied has physical and mechanical properties within the range given in Table 2. In the case of properties indicated by (+), the provision of the data is not mandatory.

### Table 1 Compositional Limits for Starting Silicon Nitride Powders or Silicon Powder Converted to Silicon Nitride

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Limits (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon nitride</td>
<td>97.0 min.</td>
</tr>
<tr>
<td>Free silicon</td>
<td>0.3 max.</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.3 max.</td>
</tr>
<tr>
<td>Iron</td>
<td>0.5 max.</td>
</tr>
</tbody>
</table>

Other impurities or elements such as sodium, potassium, chlorine, etc. individually shall not exceed 0.02 wt % max.
7. Physical Properties

7.1 The following physical properties shall be measured, at a minimum, on each material lot.

7.1.1 Average values for room temperature rupture strength (bend strength/modulus of rupture) for a minimum of 20 individual determinations shall exceed the minimum values given in Table 3. Either 3-point or 4-point test methods may be used for flexural strength, which should be measured in accordance with Test Method C1161 (size B), CEN 843-5, or JIS R 1601. Weibull modulus for each test series shall also exceed the minimum permitted values given in Table 3. A sample set of specimens for a material lot does not meet the Weibull modulus requirement in Table 3, then a second sample set may be tested to establish conformance.

**TABLE 2 Typical Mechanical Properties**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, g/cc [lb/ft³]</td>
<td>3.0 [187]</td>
<td>3.4 [212]</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.23</td>
<td>0.29</td>
</tr>
<tr>
<td>Thermal conductivity, W/m·°K [Btu/h·°F]</td>
<td>20 [11.5]</td>
<td>38 [21.9]</td>
</tr>
<tr>
<td>- @ 20°C (room temp.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific heat, J/kg·°K [Btu/lbm·°F]</td>
<td>650 [0.167]</td>
<td>800 [0.191]</td>
</tr>
<tr>
<td>Coefficient of thermal expansion, ×10⁴°C¹</td>
<td>2.3</td>
<td>3.4</td>
</tr>
<tr>
<td>(room temp. to 500°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ Resistivity, Ohm-m</td>
<td>10¹⁶</td>
<td>10¹⁶</td>
</tr>
<tr>
<td>+ Compressive strength, MPa [ksi]</td>
<td>3000 [435]</td>
<td></td>
</tr>
</tbody>
</table>

¹ Special material data should be obtained from individual suppliers.

**TABLE 3 Minimum Values for Mean Flexural Strength and Weibull Modulus**

<table>
<thead>
<tr>
<th>Transverse-rupture strength⁴</th>
<th>Unit</th>
<th>Material Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 point σ₃₄₀₀ (σ₃₃₀₀)</td>
<td>MPa</td>
<td>I</td>
</tr>
<tr>
<td>900 [920]</td>
<td>800 [825]</td>
<td>600 [625]</td>
</tr>
<tr>
<td>Weibull modulus</td>
<td>12</td>
<td>9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Transverse-rupture strength⁴</th>
<th>Unit</th>
<th>Material Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-point σ₄₄₀ (σ₄₃₀₀)</td>
<td>MPa</td>
<td>I</td>
</tr>
<tr>
<td>765 [805]</td>
<td>660 [705]</td>
<td>485 [530]</td>
</tr>
<tr>
<td>Weibull modulus</td>
<td>12</td>
<td>9</td>
</tr>
</tbody>
</table>

³ The Flexural strength equivalents are based on Weibull volume or surface scaling using the value of m for each cell and are rounded to the nearest 5 MPa.

7.1.2 The hardness (HV) shall be determined by the Vickers method (see Annex A1) using a load of at least 5 kg but not exceeding 20 kg. Fracture resistance shall be measured by either an indentation technique (see Annex A1) or by a standard fracture toughness test method. Average values for hardness and fracture resistance shall exceed the minimum of values for the specified material class given in Table 4.

7.1.3 Microstructure constituents visible at magnification in the range ×100 to ×200 shall not exceed the maximum values given in Table 5 for the specified material class.

7.1.4 The number of ceramic metallic or mixed inclusions observed in transverse sections shall not exceed the limits given in Table 6.

7.1.5 Macrostructure variation visible at 1x on a polished section is not permissible.

7.1.6 Density variation from the mean value of a sample of at least 10 pieces taken from a batch of components manufactured under the same conditions shall not exceed the values for 3 times the standard deviation (3 × sigma) given in Table 7, according to the volume of the component after any finishing operations and the specified material class. Density variation testing will apply to all lots of material for the initial 50 lots. If consistent results are achieved, the testing will be optional.

8. Inspection and Verification

8.1 The intent of this section is to list potential defects and methods of inspection of finished balls. As the spectrum of applications for silicon nitride balls is very broad, this is not intended to define requirements, but to highlight these points. The type of defects, methods of inspection, and limits should be agreed upon by the customer and vendor to meet the specific requirements for a given application.

8.2 Unless otherwise specified, all dimensional and form inspections shall be performed under the following conditions:

8.2.1 Temperature—Room ambient 20° to 25°C [68° to 77°F].

8.2.2 Humidity—50 % relative, maximum.

8.3 Unless otherwise required, product shall be capable of passing acceptance inspection in accordance with ANSI/ASQC Z1.4 as specified in Table 8.

8.4 Certain manufacturer to manufacturer or lot to lot variation in color is acceptable. Color variation within a single ball should be investigated per 8.5.

**TABLE 4 Minimum Values for Hardness and Toughness**

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Load</th>
<th>Material Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness</td>
<td>HV5</td>
<td>5 kg</td>
<td>I</td>
</tr>
<tr>
<td>HV10</td>
<td>kg/mm²</td>
<td>7</td>
<td>1500</td>
</tr>
<tr>
<td>HV20</td>
<td>20 kg</td>
<td>1480</td>
<td>1380</td>
</tr>
<tr>
<td>Indentation Fracture Resistance, IFR (or “TP”) (Annex A1)</td>
<td>MPa/m</td>
<td>6.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Fracture Toughness, KIJ (Test Methods C1421 or JIS R 16027)</td>
<td>MPa/m</td>
<td>6.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>
8.5 There may exist in silicon nitride bearing balls the defects listed in Section 8.5.1, which may be inspected for using the methods in 8.5.2 as required.

8.5.1 *Types of Defects:*

8.5.1.1 *Inclusions;*

8.5.1.2 *Porosity;*

8.5.1.3 *Pits, scratches, nicks, scuffs;*

8.5.1.4 *Cracks or linear indications; and*

8.5.1.5 *Color variation.*

8.5.2 *Methods of Inspection:*

8.5.2.1 Visual white light (unaided eye and magnification-aided eye);

8.5.2.2 Black light (unaided eye and magnification-aided eye);

8.5.2.3 Fluorescent penetrant inspection (FPI) (unaided eye and magnification-aided eye); and

8.5.2.4 Ultrasonic Inspection (The following methods are currently in development and may require extensive evaluation to be applicable):

(1) Resonant inspection (resonant ultrasound spectroscopy),

(2) Rayleigh wave, and

(3) Acoustic microscopy.

8.6 *Dimensional and Form.*

8.6.1 *Tolerances by Grade for Individual Balls and Tolerances by Grade for Lots of Balls—Tests shall be in accordance with Tables 8-10. A minimum of three measurements shall be taken in random orientations on each sample ball examined.*

8.6.2 Acceptable methods of determining errors in spherical forms include the following: roundness measuring equipment procedures and Vee Block examination procedure. Explanation and details of these methods shall be as indicated in ABMA STD-10. Tests shall be in accordance with Tables 8 and 9.

8.7 The nominal diameter of the balls shall be as specified in the contract or purchase order. Tolerance limits for size variations and form deviations shall be in accordance with Tables 9 and 10.

8.8 The surface roughness of the balls shall not exceed the value specified in Table 11 for the specified grade. Surface roughness shall be in accordance with ASME B 46.1.

9. *Certificates of Quality and Material Certification* (This section contains information of a general or explanatory nature which may be helpful but is not mandatory.)

9.1 When specified in the contract or purchase order, certificates of quality (conformance) supplied by the manufacturer of the balls may be furnished in lieu of actual performance of such testing by the manufacturer, provided the lot identity has been maintained and can be demonstrated to the customer. The certificate may include:

9.1.1 Name of the customer,

9.1.2 Contract or purchase order number,

9.1.3 Name of the manufacturer or supplier,

9.1.4 NSN (National Stock Number) item identification number,
9.1.5 Name of the material,  
9.1.6 Lot number,  
9.1.7 Lot size,  
9.1.8 Sample size,  
9.1.9 Date of testing,  
9.1.10 Test method,  
9.1.11 Individual test results, and  
9.1.12 Specification requirements.

9.2 When specified in the contract or purchase order, a certified report shall be available for review or when requested submitted by the manufacturer or supplier on each lot of balls. The report may contain the following:

9.2.1 Contract or purchase order number,  
9.2.2 Material specification number and revision,  
9.2.3 Size,  
9.2.4 Quantity,  
9.2.5 Batch identification code,  
9.2.6 Chemical analysis of silicon nitride that meets the blank manufacturer’s specification (optional),  
9.2.7 Flexural Strength (optional),  
9.2.8 Materials properties as listed in Table 2 of this specification (optional),  
9.2.9 Hardness,  
9.2.10 Fracture toughness, and  
9.2.11 Microstructure ratings.  
9.2.12 A statement that this material has been processed and tested in accordance with this specification (latest revision) and/or approved material specifications.

9.2.13 Contract or purchase order requirements other than those specified within this specification will have authority over this document.

10. Packaging

10.1 For acquisition purposes, the packaging requirements shall be as specified in the contract or order.

10.2 Preservatives are not required.

10.3 Special Handling. It is recommended that for Class I applications, balls 3/8 inch in diameter and greater should be packaged to prevent ball-to-ball contact.

11. Keywords

11.1 ball bearings; bearing balls; ceramic; silicon nitride; Si₃N₄; precision balls
A1.1 Measurements for hardness and toughness are made on a polished cross-section.

A1.2 Indentations for toughness measurement are made using a Vicker’s indenter under the following conditions:

- Load: 20 kgf
- Dwell Time: 30 s

A1.3 Hardness and toughness are calculated as follows (see Fig. A1.1):

A1.3.1 Measure both diagonals of each hardness impression as “2a” values according to orientation except when impressions are placed on separate pieces.

A1.3.2 Measure visible tip-to-tip crack lengths associated with the hardness impressions as “2c” values according to orientation except when impressions are placed on separate pieces.

A1.3.3 Calculate the mean values of 
\[ 2a = \frac{(2a_1 + 2a_2)}{2} \]
and 
\[ 2c = \frac{(2c_1 + 2c_2)}{2} \]
in micron (µm).

A1.3.4 Calculate the Vickers hardness value as follows:
\[ HV = 1.854.400 \frac{P}{(2a)^2} \]
where:
- \(HV\) = Vicker’s hardness number. The symbol should be written with the indentation load in kilograms denoted in parentheses (for example, HV(20) for a 20kgf load.)
- \(P\) = the applied load in kilogram force (kgf).
- \(a(2a/2)\) = the mean half length diagonal value in microns (µm).

A1.3.5 Calculate the indentation fracture resistance by Niihara’s method as follows:
\[ IFR = 10.4 \left( \frac{E^{0.4}}{P^{0.6}} \right) \left( \frac{a^{0.8}}{c^{1.5}} \right) \]
where:
- \(IFR\) = the indentation fracture resistance in megapascals–square root meter (Mpa-m½)
- \(E\) = the elastic modulus in gigapascals (Gpa).
- \(P\) = the applied load in kilogram force (kgf).
- \(a\) = the mean half diagonal value in microns (µm).
- \(c\) = the mean half tip-to-tip crack length in microns (µm).

A1.4 Alternative formulas or calibration constants for indentation fracture resistance may be used by mutual agreement of customer and vendor.
Note A1.1—The within-lab (repeatability) consistency of results by this method may be acceptable, but the between-laboratory (reproducibility) consistency is often poor due to variations in the interpretation of the crack length arising from microscopy limitations as well as operator experience or subjectivity.

APPENDIX

(Nonmandatory Information)

X1. Examples of Typical Current Markets (Arrows Indicate Potential Overlap)

<table>
<thead>
<tr>
<th>Class I</th>
<th>Grade 2, 3</th>
<th>Grade 5</th>
<th>Grade 10, 16</th>
<th>Grade 24, 48</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Speed</td>
<td>Space Mechanism</td>
<td>Lox Pump</td>
<td>Mainshaft Bearing</td>
<td>Critical Aircraft Parts</td>
</tr>
<tr>
<td>Momentum</td>
<td>Aircraft Instrumentation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Device</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Class II</th>
<th>Grade 2, 3</th>
<th>Grade 5</th>
<th>Grade 10, 16</th>
<th>Grade 24, 48</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbo</td>
<td>Vacuum Equipment</td>
<td>Machine</td>
<td>Electric Motors</td>
<td>Check Balls Single Balls</td>
</tr>
<tr>
<td>Molecular</td>
<td></td>
<td>Tool Spindle</td>
<td>Med/Low Precision Radial Bearing</td>
<td></td>
</tr>
<tr>
<td>Pump</td>
<td></td>
<td>High Performance Angular Contact</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Precision</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radial Bearing</td>
<td>Dental Drill</td>
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</table>

<table>
<thead>
<tr>
<th>Class III</th>
<th>Grade 2, 3</th>
<th>Grade 5</th>
<th>Grade 10, 16</th>
<th>Grade 24, 48</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Sports &amp; Recreation</td>
<td>Food Processing</td>
<td></td>
<td>Mechanical Devices</td>
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<td></td>
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</tbody>
</table>

FIG. X1.1 Examples of Typical Current Markets (Arrows Indicate Potential Overlap)
RELATED MATERIAL

ASTM Standards:
- C373 Test Method for Water Absorption, Bulk Density, Apparent Porosity, and Apparent Specific Gravity of Fired Whiteware Products
- C1198 Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio for Advanced Ceramics by Sonic Resonance
- C1239 Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Ceramics
- C1327 Test Method for Vickers Indentation Hardness of Advanced Ceramics
- E165 Test Method for Liquid Penetrant Examination
- E384 Test Method for Microindentation Hardness of Materials
- E831 Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis
- E1417 Practice for Liquid Penetrant Testing

ABMA Standards: STD 1 Terminology for Anti-Friction Ball and Roller Bearings and Parts

DIN Standards:
- 5401 Rolling Bearings; Balls of Through-Hardening Rolling Bearing Steel, Part 1
- 5401 Rolling Bearings; Balls of Through-Hardening Rolling Bearing Steel, Part 2

ISO Standards:
- 3290 Rolling Bearings, Bearing Parts, Balls for Rolling Bearings

JIS Standards:
- R 1602 Testing Method for Elastic Modulus of High Performance Ceramics

CEN Standards:
- EN 843-2 Advanced Technical Ceramics—Monolithic Ceramics—Mechanical Properties at Room Temperature, Part 2 Determination of Elastic Moduli
- EN 621-2 Advanced Technical Ceramics—Monolithic Ceramics—Thermo-physical Properties—Part 2: Determination of Thermal Diffusivity by the Laser Flash (or Heat Pulse) method
- EN 821-1 Advanced Technical Ceramics—Monolithic Ceramics—Thermo-physical Properties—Part 1: Determination of Thermal Expansion

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