Designation: F 2094 – 01a

Standard Specification for Silicon Nitride Bearing Balls[1]

This standard is issued under the fixed designation F 2094; 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 are not exact equivalents; therefore, each system must be used independently of the other. Combining values from the two systems may result in nonconformance with the specification.

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:*

C 373 Test for Water Absorption, Bulk Density[2]

C 1161 Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature[3]

C 1198 Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio for Advanced Ceramics by Sonic Resonance[3]

C 1239 Practice for the Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Ceramics[3]

C 1327 Test Method for Vickers Indentation Hardness of Advanced Ceramics[3]

C 1421 Test Methods for the Determination of Fracture Toughness of Advanced Ceramic Materials at Ambient Temperatures[3]

E 165 Test Method for Liquid Penetrant Examination[4]

E 384 Test Method for Microhardness of Materials[5]

E 831 Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis[6]

E 1417 Practice for Liquid Penetrant Examination[4]

2.3 *ANSI Standard:*

ANSI/ASQC Z1.4 Sampling Procedures and Tables for Inspection by Attributes[7]

2.4 *ABMA Standards:*

STD 1 Terminology for Anti-Friction Ball and Roller Bearings and Parts[8]

STD 10 Metal Balls[8]

2.5 *ASME Standard:*

B 46.1 Surface Texture (Surface Roughness, Waviness, and Lay)[9]

2.6 *DIN Standards:*[10]

5401 Rolling Bearings; Balls of Through-Hardening Rolling Bearing Steel, Part 1

5401 Rolling Bearings; Balls of Through-Hardening Rolling Bearing Steel, Part 2

2.7 *ISO Standards:*

3290 Rolling Bearings, Bearing Parts, Balls for Rolling Bearings[11]

4505 Hardmetals—Metallographic Determination of Porosity and Uncombined Carbon[11]

2.8 *JIS Standards:*

R 1601 Testing Method for Flexural Strength (Modulus of Rupture) of High Performance Ceramics[12]

R 1602 Testing Method for Elastic Modulus of High Performance Ceramics[12]

R 1603 Methods for Chemical Analysis of Fine Silicon Nitride Powders for Fine Ceramics[12]

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[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 Elements.

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[2] *Annual Book of ASTM Standards*, Vol 15.02.

[3] *Annual Book of ASTM Standards*, Vol 15.01.

[4] *Annual Book of ASTM Standards*, Vol 03.03.

[5] *Annual Book of ASTM Standards*, Vol 03.01.

[6] *Annual Book of ASTM Standards*, Vol 14.02.

[7] Application for copies should be addressed to the American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036.

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

[9] Application for copies should be addressed to the American Society of Mechanical Engineers, 345 East Street, New York, NY 10017.

[10] Application for copies should be addressed to the Deutsches Institut Für Normung (German Standards Institute), Burggrafenstrasse 6, D 10787 Berlin, Germany.

[11] Application for copies should be addressed to the American National Standards Institute, 11 West 42nd Street, New York, NY 10036-8002.

[12] Application for copies should be addressed to the Japanese Standards Association, 1-24 Akasaka 4 chome, Minato-ku, Tokyo. 107 Japan.

R 1607 Testing Method for Fracture Toughness of High Performance Ceramics[12]

R 1610 Testing Method for Vicker's Hardness of High Performance Ceramics[12]

R 1611 Testing Methods of Thermal Diffusivity, Specific Heat Capacity and Thermal Conductivity for High Performance Ceramics by Laser Flash Method[12]

R 1618 Measuring method of thermal expansion of fine ceramics by thermomechanical analysis[12]

R 1624 Weibull Statistics of Strength Data for Fine Ceramics[12]

2.9 *CEN Standards:*

EN 843-1 Advanced Technical Ceramics—Monolithic Ceramics—Mechanical Properties at Room Temperature, Part 1. Determination of Flexural Strength[13]

EN 843-2 Advanced Technical Ceramics—Monolithic Ceramics—Mechanical Properties at Room Temperature, Part 2 Determination of Elastic Moduli[13]

ENV 843-4 Advanced Technical Ceramics—Monolithic Ceramics—Mechanical Properties at Room Temperature, Part 4. Vickers, Knoop and Rockwell Superficial Hardness Tests[13]

ENV 843-5 Advanced Technical Ceramics—Monolithic Ceramics—Mechanical Properties at Room Temperature, Part 5, Statistical Analysis[13]

EN 623-2 Advanced Technical Ceramics—Monolithic Ceramics—General and Textural Properties—Determination of Density and Porosity[13]

EN 821-2 Advanced Technical Ceramics—Monolithic Ceramics—Thermo-physical Properties—Part 2: Determination of Thermal Diffusivity by the Laser Flash (or Heat Pulse) method[13]

EN 821-1 Advanced Technical Ceramics—Monolithic Ceramics—Thermo-physical Properties—Part 1: Determination of Thermal Expansion[13]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *ball diameter variation*, *n*—ball diameter variation is the difference between the largest and smallest diameter measured on the same ball.

3.1.2 *ball gage*, *n*—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*, *n*—difference between the lot mean diameter and the sum of the nominal diameter and the ball gage.

3.1.4 *ball grade*, *n*—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 *basic diameter*, *n*—size ordered that is the basis to which the basic diameter tolerances apply. The basic diameter is specified in inches or millimeters (decimal form).

3.1.6 *basic diameter tolerance*, *n*—maximum allowable deviation from true specified basic diameter for the indicated grade.

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

3.1.8 *deviation from spherical form*, *n*—greatest radial distance in any radial plane between a sphere circumscribed around the ball surface and any point on the ball surface.

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

3.1.10 *lot diameter variation*, *n*—difference between the mean diameter of the largest ball and that of the smallest ball in the lot.

3.1.11 *lot mean diameter*, *n*—arithmetic mean of the mean diameter of the largest ball and that of the smallest ball in the lot.

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

3.1.13 *mean diameter of a ball*, *n*—arithmetic mean of the largest and the smallest actual single diameters of the ball.

3.1.14 *nominal size*, *n*—size that is used for the purpose of general identification, for example, 1⁄16, 1⁄8, etc.

3.1.15 *specific diameter*, *n*—diameter marked on the unit container and expressed in the grade standard marking increment nearest to the average diameter of the balls in the container.

3.1.16 *unit container*, *n*—container identified as containing balls from the same manufacture lot of the same composition, grade, and basic 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:[14]

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.

[13] Application for copies should be addressed to the British Standards Institute, 389 Chiswick High Road, London, W4 4AL, UK.

[14] See Appendix X1 for typical current applications.

5.1.2 Class, grade, and size (see 4.1 and 8.6)

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 The following compounds may be added to promote densification and/or enhance product performance and quality. The following may be added as oxides, nitrides, oxynitrides, or mixtures:

6.4.1 Aluminum,
6.4.2 Magnesium,
6.4.3 Barium,
6.4.4 Lanthanum,
6.4.5 Yttrium,
6.4.6 Calcium, and
6.4.7 Other rare earths.

6.5 The following may be added as nitrides, oxynitrides, or carbonites:

6.5.1 Titanium,
6.5.2 Tantalum, and
6.5.3 Zirconium.

6.6 Aluminum silicon oxynitrides (aluminum nitride polytypes) may be added to promote densification.

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

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

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

6.10 Notification will be made upon process changes.

6.11 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.

6.12 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[A]

Constituents	Limits (wt %)
Silicon nitride	97.0 min.
Free silicon	0.3 max.
Carbon	0.3 max
Iron	0.1 max.

[A] Other impurities or elements such as sodium, potassium, chlorine, etc. individually shall not exceed 0.02 wt % max.

TABLE 2 Typical Mechanical Properties[A]

Properties	Minimum	Maximum
Density, g/cc (lb/ft^3)	3.0 (187)	3.4 (212)
Elastic modulus, GPa (ksi)	270 (39 150)	330 (47 850)
Poisson's ratio	0.23	0.29
Thermal conductivity, W/m-°K (Btu/h-ft-°F) – @ 20°C (room temp.)	20 (11.5)	38 (21.9)
Specific heat, J/kg-°K (Btu/1bm-°F)	650 (0.167)	800 (0.191)
Coefficient of thermal expansion, $\times 10^6$/°C (room temp. to 500°C)	2.3	3.4
+ Resistivity, Ohm-m	10^{10}	10^{16}
+ Compressive strength, MPa (ksi)	3000 (435)	

[A] Special material data should be obtained from individual suppliers.

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 ASTM C 1161 (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. If 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.

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

TABLE 3 Minimum Values for Mean Flexural Strength and Weibull Modulus

	Unit	Material Class		
		I	II	III
Transverse-rupture strength[A] 3 point $\sigma_{3,40}(\sigma_{3,30})$	MPa	900 (920)	800 (825)	600 (625)
Weibull modulus		12	9	7
Transverse-rupture strength[A] 4-point $\sigma_{4,40}(\sigma_{4,30})$	MPa	700 (745)	600 (645)	450 (495)
Weibull modulus		10	8	6

[A] 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.

$\sigma_{n,L}$ = denotes the flexure strength, n = 3 or 4 point, on spans of size L.

$\sigma_{4,40}$ = 660 MPa means the four point flexure strength, on 40 mm spans is 660 MPa as per ASTM C 1161 (size B) and CEN EN 843-1.

$\sigma_{4,30}$ = 700 MPa means the four point flexure strength, on 30 mm spans is 700 MPa as per JIS R1601.

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 1× 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.

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;

TABLE 4 Minimum Values for Hardness and Toughness

Property	Unit	Load	Material Class I	II	III
Hardness HV5		5 kg	1500	1400	1350
HV10	kg/mm^2	10 kg	1480	1380	1325
HV20		20 kg	1460	1360	1300
Indentation Fracture Resistance, IFR (or "TP") (Annex A1)	MPa$\sqrt{m}$		6.0	5.0	5.0
Fracture Toughness, K_{Ic} (ASTM C 1421 or JIS R 1607)	MPa$\sqrt{m}$		6.0	5.0	5.0

TABLE 5 Maximum Limits for Microstructural Constituents

	Material Class I	II	III
Porosity: Size (µm)	10	10	25
Volume Rating / ISO 4505	0.02	0.06	0.06
Metallic Phases: Size (µm)	10	10	25
Ceramic 2nd Phases: Size (µm)	25	25	25

TABLE 6 Maximum Number of Inclusions per cm^2 of Transverse Section

Maximum Extent in µm	Material Class I	II	III
200	0	0	1
100 to <200	0	1	2
50 to <100	1	2	4
25 to <50	4	8	16

TABLE 7 Maximum Allowable Density Variation (3 × Sigma) Within a Single Lot

Ball Diameter in Inches (mm)	Density Variation (g/cm^3) Material Class I	II	III
3/32 to <15/64 (2.38 to <5.95)	0.010	0.015	0.020
15/64 to <13/32 (5.95 to 10.32)	0.008	0.010	0.015
13/32 to <5/8 (10.32 to <15.88)	0.005	0.008	0.012
5/8 to 15/16 (15.88 to 33.34)	0.005	0.005	0.010

TABLE 8 Quality Conformance Inspections

Requirement	Inspection Level	AQL
Quality of geometry (see 8.6 for limits)	S4^A	0.4 %
Quality of surface (see 8.4 for tolerances)	S4	0.4 %
Surface roughness	Use sample size shown below and accept lot if all test results are within specifications	
	Number of Balls per Lot	Sample Size
	0–35 000	5
	35 001 and over	8

^{A} Minimum sample size of 32 balls shall apply only to lots of 1200 or more pieces. For lots of less than 1200, sample size shall be set by agreement between manufacturer and customer.

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

TABLE 9 Tolerances by Grade for Individual Balls Micrometers (Micro-inches)

Grade	Allowable Ball Diameter Variation V_D	Allowable Deviation from Spherical Form W
2C	0.05 (2)	0.05 (2)
3C	0.08 (3)	0.08 (3)
5C	0.13 (5)	0.13 (5)
10C	0.25 (10)	0.25 (10)
16C	0.40 (16)	0.40 (16)
24C	0.61 (24)	0.61 (24)
48C	1.22 (48)	1.22 (48)

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 3 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 basic 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 ⅜ 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; Si_3N_4; precision balls

TABLE 10 Tolerances by Grade for Lots of Balls Micrometers (Micro-inches)

Grade	Allowable Lot Diameter Variation	Basic Diameter Tolerance	Allowable Ball Gage Deviation	
			High	Low
2C	0.08 (3)	±.51 (±20)	+.51 (+20)	–.51 (–20)
3C	0.13 (5)	±.51 (±20)	+.51 (+20)	–.51 (–20)
5C	0.25 (10)	±.76 (±30)	+.76 (+30)	–.76 (–30)
10C	0.51 (20)	±2.54 (±100)	+1.27 (+50)	–1.02 (–40)
16C	0.80 (32)	±2.54 (±100)	+1.27 (+50)	–1.02 (–40)
24C	1.22 (48)	±2.54 (±100)	+2.54 (+100)	–2.54 (–100)
48C	2.44 (96)	N/A	N/A	N/A

TABLE 11 Surface Roughness by Grade for Individual Balls

Grade	Maximum Surface Roughness Arithmetical Average Micrometers (Micro-inches)
2C	0.004 (0.15)
3C	0.004 (0.15)
5C	0.005 (0.20)
10C	0.006 (0.25)
16C	0.009 (0.35)
24C	0.013 (0.50)
48C	0.013 (0.50)

ANNEX

(Mandatory Information)

A1. VICKER'S HARDNESS AND NIIHARA'S TOUGHNESS MEASUREMENTS

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 "2*a*" 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 "2*c*" values according to orientation except when impressions are placed on separate pieces.

A1.3.3 Calculate the mean values of $2a = (2a_1 + 2a_2)/2$ and $2c = (2c_1 = 2c_2)/2$ in micron (μm).

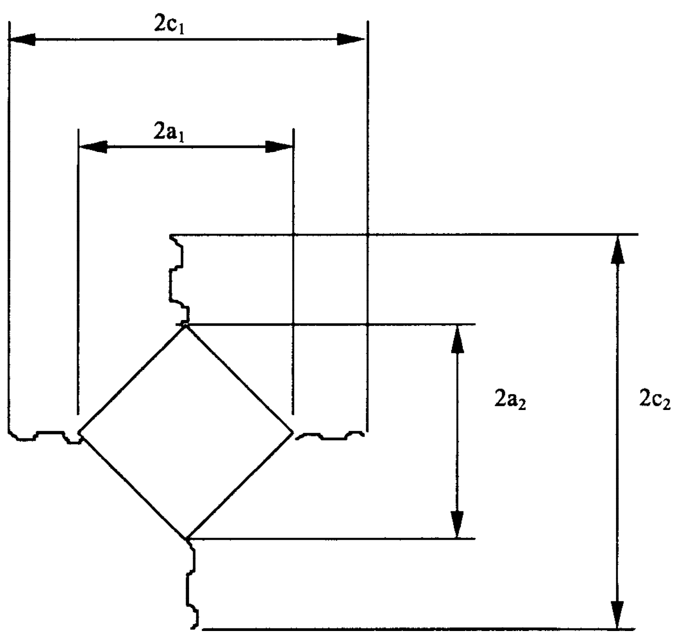
A1.3.4 Calculate the Vickers hardness value as follows:

$$HV = 1{,}854{,}400\ P/(2a)^2$$

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:



$$2a = \frac{(2a_1 + 2a_2)}{2}$$

$$2c = \frac{(2c_1 + 2c_2)}{2}$$

FIG. A1.1 Hardness and Toughness Calculation

$$IFR = 10.4\ (E^{0.4})\ (P^{0.6})\ (a^{0.8}/c^{1.5})$$

where:

IFR = the indentation fracture resistance in megapascals–square root meter (Mpa-$m^{1/2}$)
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)

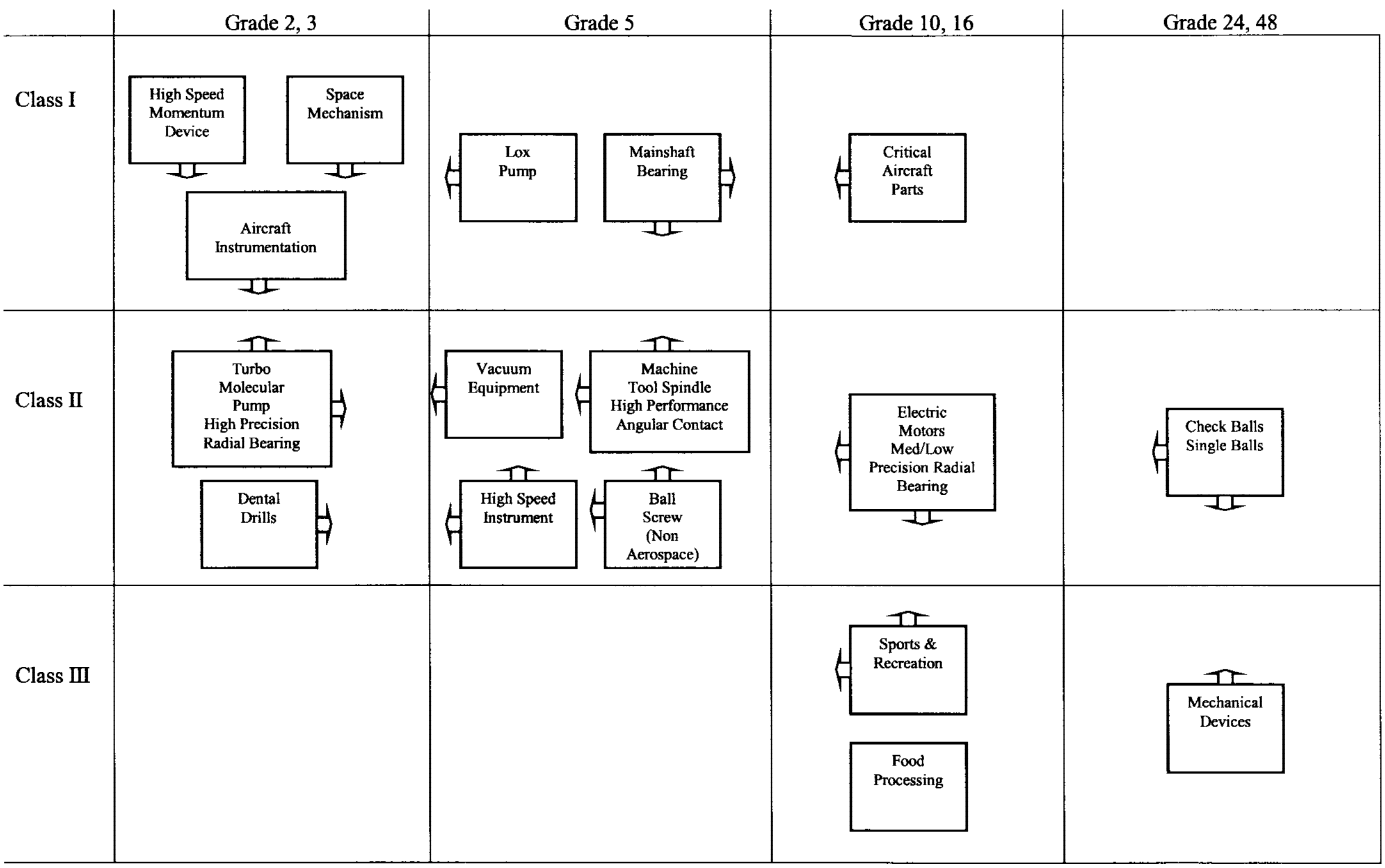


FIG. X1.1 Examples of Typical Current Markets (Arrows Indicate Potential Overlap)