Designation: C1495 – 16 (Reapproved 2023)

Standard Test Method for Effect of Surface Grinding on Flexure Strength of Advanced Ceramics[1]

This standard is issued under the fixed designation C1495; 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 test method covers the determination of the effect of surface grinding on the flexure strength of advanced ceramics. Surface grinding of an advanced ceramic material can introduce microcracks and other changes in the near surface layer, generally referred to as damage (see Fig. 1 and Ref. (**1**)).[2] Such damage can result in a change—most often a decrease—in flexure strength of the material. The degree of change in flexure strength is determined by both the grinding process and the response characteristics of the specific ceramic material. This method compares the flexure strength of an advanced ceramic material after application of a user-specified surface grinding process with the baseline flexure strength of the same material. The baseline flexure strength is obtained after application of a surface grinding process specified in this standard. The baseline flexure strength is expected to approximate closely the inherent strength of the material. The flexure strength is measured by means of ASTM flexure test methods.

1.2 Flexure test methods used to determine the effect of surface grinding are C1161 Test Method for Flexure Strength of Advanced Ceramics at Ambient Temperatures and C1211 Test Method for Flexure Strength of Advanced Ceramics at Elevated Temperatures.

1.3 Materials covered in this standard are those advanced ceramics that meet criteria specified in flexure testing standards C1161 and C1211.

1.4 The flexure test methods supporting this standard (C1161 and C1211) require test specimens that have a rectangular cross section, flat surfaces, and that are fabricated with specific dimensions and tolerances. Only grinding processes that are capable of generating the specified flat surfaces, that is, planar grinding modes, are suitable for evaluation by this method. Among the applicable machine types are horizontal and vertical spindle reciprocating surface grinders, horizontal and vertical spindle rotary surface grinders, double disk grinders, and tool-and-cutter grinders. Incremental cross-feed, plunge, and creep-feed grinding methods may be used.

1.5 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

C1145 Terminology of Advanced Ceramics
C1161 Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature
C1211 Test Method for Flexural Strength of Advanced Ceramics at Elevated Temperatures
C1239 Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Ceramics
C1322 Practice for Fractography and Characterization of Fracture Origins in Advanced Ceramics
C1341 Test Method for Flexural Properties of Continuous Fiber-Reinforced Advanced Ceramic Composites

3. Terminology

3.1 *Materials Related:*

[1] This test method is under the jurisdiction of ASTM Committee C28 on Advanced Ceramics and is the direct responsibility of Subcommittee C28.01 on Mechanical Properties and Performance.

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[2] The boldface numbers in parentheses refer to a list of references at the end of this standard.

[3] 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.

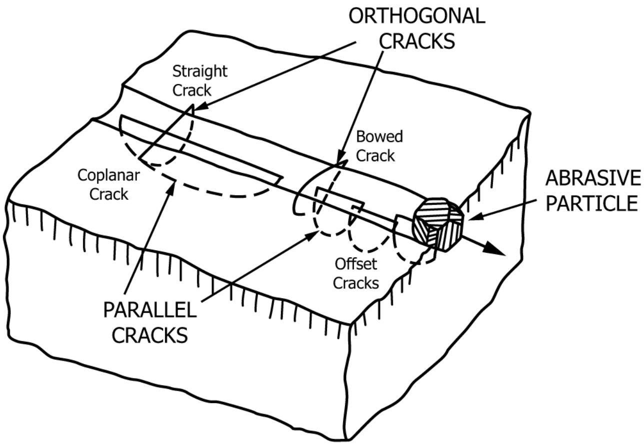

FIG. 1 Microcracks Associated with Grinding (Ref. (1))[2]

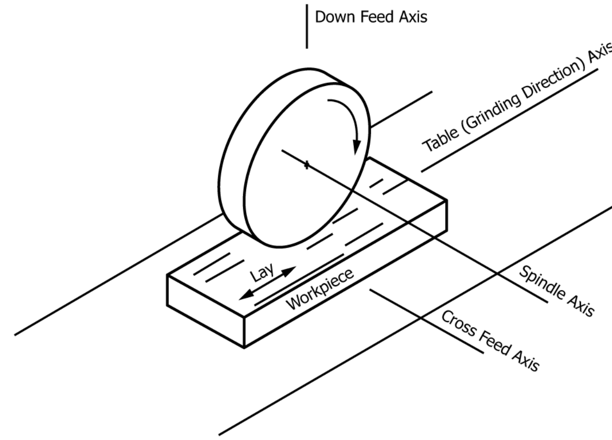

FIG. 2 Machine Axes for Horizontal Spindle Reciprocating Surface Grinder

3.1.1 *advanced ceramic, n*—a highly engineered, high-performance, predominately nonmetallic, inorganic, ceramic material having specific functional attributes. **C1145**

3.1.2 *baseline flexure strength, n*—in the context of this standard, refers to the flexure strength value obtained after application of a grinding procedure specified in this standard.

3.1.2.1 *Discussion*—For the advanced ceramics to which this standard is applicable, the baseline flexure strength is expected to be a close approximation to the inherent flexure strength.

3.1.3 *ceramic matrix composite, n*—a material consisting of two or more materials (insoluble in one another) in which the major, continuous component (matrix component) is a ceramic, while the secondary component(s) (reinforcing component) may be ceramic, glass-ceramic, glass, metal, or organic in nature. These components are combined on a macroscale to form a useful engineering material possessing certain properties or behavior not possessed by the individual constituents. **C1341**

3.1.4 *grinding damage, n*—any change in a material that is a result of the application of a surface grinding process. Among the types of damage are microcracks (Fig. 1), dislocations, twins, stacking faults, voids, and transformed phases.

3.1.4.1 *Discussion*—Although they do not represent internal changes in microstructure, chips and surface pits, which are a manifestation of microfracture, and abnormally large grinding striations are often referred to as grinding damage. Residual stresses that result from microstructural changes may also be referred to as grinding damage.

3.1.5 *inherent flexure strength, n*—the flexure strength of a material in the absence of any effects of surface grinding or other surface finishing process, or of extraneous damage that may be present. The measured inherent flexure strength may depend on the flexure test method, test conditions, and test specimen size.

3.1.5.1 *Discussion*—Flaws due to surface finishing or extraneous damage may be present but their effect on flexure strength is negligible compared to that of "inherent" flaws in the material.

3.1.6 *materials lot or batch, n*—a single billet or several billets prepared from defined homogeneous quantities of raw materials passing simultaneously through each processing step to the end product is often referred to as belonging to a single lot or batch.

3.1.6.1 *Discussion*—There is no assurance that a single billet is internally homogenous or that billets belonging to the same lot or batch are identical.

3.2 *Grinding Process Related*—Definitions in this section apply to grinding machines and modes that generate planar surfaces. Applicable grinding machines types are identified in (1.4). Some definitions may not be applicable when used in connection with non-planar grinding modes such as centerless and cylindrical modes which are outside of the scope of this standard.

3.2.1 *blanchard grinding, n*—a type of rotary grinding in which the workpiece is held on a rotating table with an axis of rotation that is parallel to the (vertical) spindle axis.

3.2.2 *coolant, n*—usually a liquid that is applied to the workpiece or wheel, or both, during grinding for cooling, removal of grinding swarf, and for lubrication.

3.2.3 *coolant flow rate, n*—volume of coolant per unit time delivered to the wheel and workpiece during grinding.

3.2.4 *creep-feed grinding, n*—a mode of grinding characterized by a relatively large wheel depth-of-cut and correspondingly low rate of feed.

3.2.5 *cross-feed, n*—increment of displacement or feed in the cross-feed direction.

3.2.6 *cross-feed direction, n*—direction in the plane of grinding which is perpendicular to the principal direction of grinding. (Fig. 2)

3.2.7 *down-feed, n*—increment of displacement or feed in the down feed direction. (Fig. 2)

3.2.8 *down-feed direction, n*—direction perpendicular to the plane of grinding for a machine configuration in which the grinding wheel is located above the workpiece. (Fig. 2)

3.2.9 *down-grinding, n*—A condition of down-grinding is said to hold when the velocity vector tangent to the surface of

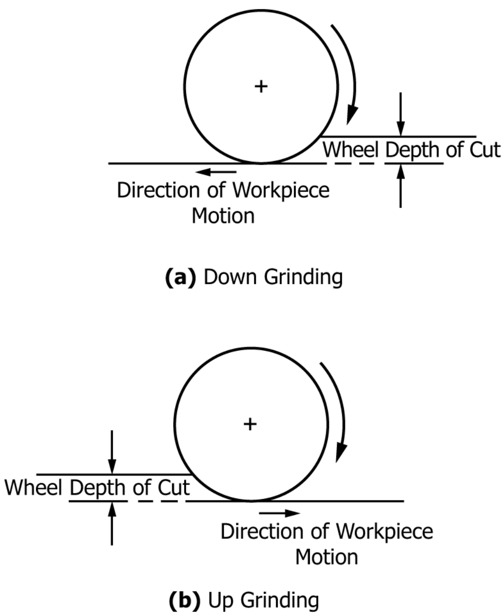

FIG. 3 Relative Wheel and Workpiece Directions of Motion for Down Grinding and Up Grinding

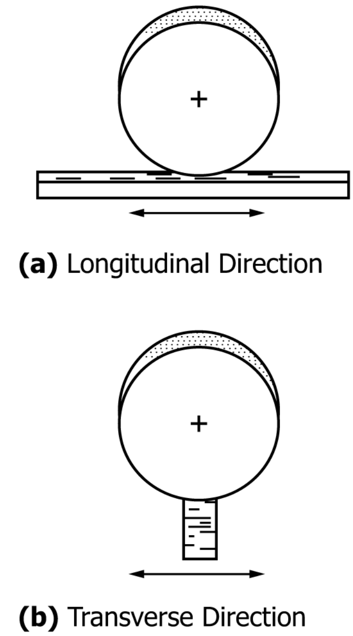

FIG. 4 Grinding Directions with Respect to Flexure Bar Orientation

the wheel at points of first entry into the grinding zone has a component normal to and directed into the ground surface of the workpiece. (Fig. 3a)

3.2.10 *dressing, n*—a conditioning process applied to the abrasive surface of a grinding wheel to improve the efficiency of grinding.

3.2.10.1 *Discussion*—Dressing may accomplish one or more of the following: (*1*) removal of bond material from around the grit on the surface of the grinding wheel causing the grit to protrude a greater distance from the surrounding bond, (*2*) removal of adhered workpiece material which interferes with the grinding process, removal of worn grit, (*3*) removal of bond material thereby exposing underlying unworn grit, and (*4*) fracture of worn grit thereby generating sharp edges.

3.2.11 *grinding axis, n*—any reference line along which the workpiece is translated or about which it is rotated to effect the removal of material during grinding.

3.2.12 *grinding direction, n*—when used in reference to flexure test bars, refers to the angle between the long (tensile) axis of the flexure bar and the path followed by grit in the grinding wheel as they move across the ground surface. See longitudinal grinding direction and transverse grinding direction. (Fig. 4)

3.2.13 *grit depth-of-cut, n*—nominal maximum depth that individual grit on the grinding wheel penetrate the workpiece surface during grinding. Synonymous with undeformed chip thickness.

3.2.14 *in-feed, n*—synonymous with wheel depth-of-cut and down feed.

3.2.15 *longitudinal grinding direction, n*—grinding direction parallel to the long axis of the flexure bar. (Fig. 4a)

3.2.16 *machine axes, n*—reference line along which translation or about which rotation of a grinding machine component (table, stage, spindle...) takes place. (Fig. 2)

3.2.17 *planar grinding, n*—a grinding process which generates a nominally flat (plane) surface.

3.2.18 *reciprocating grinding, n*—mode of grinding in which the grinding path consists of a series of linear bi-directional traverses across the workpiece surface.

3.2.19 *rotary grinding, n*—modes of planar grinding in which the grinding path in the plane of grinding is an arc, effected either by rotary motion of the workpiece or of the grinding wheel.

3.2.19.1 *Discussion*—Grinding striations left on the workpiece surfaces are arcs.

3.2.20 *surface grinding, n*—a grinding process used to generate a flat surface by means of an abrasive tool (grinding wheel) having circular symmetry with respect to an axes about which it is caused to rotate. (Fig. 2)

3.2.21 *table speed, n*—speed of the grinding machine table carrying the workpiece usually measured with respect to the machine frame.

3.2.22 *transverse grinding direction, n*—grinding direction perpendicular to the long axis of the flexure bar. (Fig. 4b)

3.2.23 *truing, n*—process by which the abrasive surface of a grinding wheel is brought to the desired shape and is made concentric with the machine spindle axis of rotation.

3.2.24 *undeformed chip thickness, n*—maximum thickness of a chip removed during grinding, assuming that the chip is displaced from the surface without deformation or change in shape.

3.2.24.1 *Discussion*—Equivalent in size to grit depth-of-cut.

3.2.25 *up-grinding, n*—a condition of up-grinding is said to hold when the velocity vector tangent to the surface of the wheel at points of first entry into the grinding zone has a component normal to and directed out of the ground surface of the workpiece. (Fig. 3b)

3.2.26 *wheel depth-of-cut, n*—depth of penetration of the grinding wheel into the workpiece surface as it moves parallel to the surface to remove a layer of material. (Fig. 3)

3.2.26.1 *Discussion*—Often abbreviated to depth-of-cut.

3.2.27 *wheel specifications, n*—description of the grinding wheel dimensions, grit type, grit size, grit concentration, bond type, and any other properties provided by the wheel manufacturer that characterize the grinding wheel.

3.2.28 *wheel surface speed, n*—circumferential speed of the grinding wheel surface at points which engage the workpiece during the process of grinding.

3.3 *Surface Finish Related:*

3.3.1 *lay, n*—refers to the direction a non-random pattern of surface roughness in the plane of the surface, for example, the direction of abrasive striations on a surface prepared by grinding. (Fig. 2)

3.3.2 *roughness, n*—three-dimensional variations in surface topography characterized by wavelengths in the plane of the surface that are small compared to the design dimensions of the workpiece.

3.3.3 *waviness, n*—surface topographic variations characterized by wavelengths in the plane of the surface that are large compared to the roughness but smaller than the design dimensions of the workpiece.

3.4 *Flexure Test Related:*

3.4.1 *break force, n*—force at which a test specimen fractures (fails) in a flexure test.

3.4.2 *flexural strength, n*—a measure of the ultimate strength of a specified beam in bending. **C1145**

3.4.3 *tensile face, n*—side of a flexure test specimen that is stressed in tension in a flexure test.

Other terms related to flexure testing can be found in C1161.

3.5 *Fractography Related:*

3.5.1 *crack, n*—as used in fractography, a plane of fracture without complete separation. **C1322**

3.5.2 *flaw, n*—a structural discontinuity in an advanced ceramic body which acts as a highly localized stress riser. **C1322**

3.5.3 *fractography, n*—means and methods for characterizing a fractured test specimen or component. **C1145**

3.5.4 *fracture origin, n*—the source from which brittle fracture commences. **C1145**

3.5.5 *fracture mirror, n—as used in fractography of brittle materials*, a relatively smooth region in the immediate vicinity of and surrounding the fracture origin. **C1322**

Other terms related to fractography can be found in C1322.

3.6 *Statistical Analysis Related:* Terminology related to the reporting of flexural strength data and Weibull distribution parameters can be found in C1239.

4. Summary of Test Method

4.1 This method compares the flexure strength of an advanced ceramic material that has been subjected to a user-applied surface grinding process with the baseline flexure strength for the same material. The baseline flexure strength is obtained after application of a grinding process specified in this standard and is expected to approximate closely the inherent flexure strength of the material. The user-applied surface grinding process may result in a decrease in flexure strength, no change in flexure strength, or in certain cases an increase in flexure strength. Two procedures, A and B, are available depending on the objective of the measurement. Procedure A is restricted to linear grinding processes obtained, for example, by a horizontal spindle, reciprocating-table surface grinder. In linear grinding processes, the surface finish is usually characterized by straight, parallel striations. Procedure A compares the baseline flexure strength of a material with the flexure strength (*1*) after grinding parallel (termed longitudinal) to the long axis of the flexure test specimen and (*2*) after grinding perpendicular (termed transverse) to the long axis of the flexure test specimen using the same grinding conditions. These two directions are employed because many advanced ceramics exhibit a change in flexure strength that is a minimum when grinding is in the longitudinal direction and a maximum when grinding is in the transverse direction. The grinding processes to be evaluated need only be applied to the tensile face of the test specimen. However, the other faces, especially the adjacent sides, must be prepared in such a way that they do not sustain damage that will influence the fracture process that occurs on the tensile face. (Where a grinding process could result in a substantial loss in flexure strength, it is recommended that this process not be applied to adjacent faces.) Procedure A is useful for obtaining detailed information on the response of a material to surface grinding and for the systematic determination of the influence of different grinding parameters on flexure strength. Three sets of test specimens (typically 10 to 30 test specimens per set depending on statistical requirements) will be required to evaluate a single grinding condition. Once the baseline strength is determined, only two sets, longitudinal and transverse, will be required for evaluation of additional grinding conditions, provided there is no change in the material from which the test specimens are prepared.

4.2 Procedure B is designed mainly for quality control purposes but it may also be used for process development purposes. This procedure is not restricted to linear grinding. As in Procedure A, the flexure strength of test specimens ground under user specified conditions is compared with the baseline flexure strength of the same lot of material. Procedure B is applicable to any grinding method that generates a suitably flat surface to meet the geometrical requirements for flexure test specimens (1.4). The ground surface lay may consist of a straight-line pattern generated by linear grinding, arcs produced by rotary modes of grinding, or any other pattern. However, as in Procedure A, careful consideration must be given to the directionality of the lay with respect to the tensile direction of the flexure test specimen. When different grinding parameters or different materials are to be compared, care must be taken to maintain the angle between the lay direction and the test specimen axis for all test specimens. Alternatively, similar to Procedure A, tests may be conducted to determine the relationship between lay direction with respect to the test specimen axis and flexure strength.

5. Significance and Use

5.1 Surface grinding can cause a significant decrease[4] in the flexure strength of advanced ceramic materials. The magnitude of the loss in strength is determined by the grinding conditions and the response of the material. This test method can be used to obtain a detailed characterization of the relationship between grinding conditions and flexure strength for an advanced ceramic material. The effect on flexure strength of varying a single grinding parameter or several grinding parameters can be measured. The method may also be used to compare and rank different materials according to their response to one or more different grinding conditions. Results obtained by this method can be used to develop an optimum grinding process with respect to maximizing material removal rate for a specified flexure strength requirement. The test method can assist in the development of improved grinding-damage-tolerant ceramic materials. It may also be used for quality control purposes to monitor and assure the consistency of a grinding process in the fabrication of parts from advanced ceramic materials. The test method is applicable to grinding methods that generate a planar surface and is not directly applicable to grinding methods that produce non-planar surfaces such as cylindrical and centerless grinding.

6. Interferences

6.1 The condition and properties of the grinding machine and grinding wheel can have a significant influence on the measured flexure strength. These conditions and properties may not be easily identified, measured or controlled. Machine characteristics such as static and dynamic stiffness can have a substantial effect on damage introduced by grinding. These characteristics are likely to differ for different grinding machines. Grinding wheel specifications give only a qualitative identification and not a detailed or precise measure of properties. Thus despite having common specifications, grinding wheels from different manufacturers may give different results. Wheels from the same manufacturer with the same specifications may also perform differently due to manufacturing process variations. Grinding wheel condition, which is highly sensitive to prior use and the truing and dressing procedure and cycle, can also affect flexure strength. In connection with truing and dressing, the greatest variation is likely to occur when these procedures are performed manually by the operator.

6.2 Property variations in the test material may lead to differences in flexure strength. Such variations may be associated with differences in the population of inherent flaws in the material or to compositional and microstructural variations. When the influence of machining damage on flexure strength competes with the effect of inherent flaws, a material related variation in flaw population could be mistakenly attributed to an effect of machining.

TABLE 1 Flexure Test Specimen Configurations, Dimensions, and Tolerances[A]

Configuration	Width (b), mm	Depth (d), mm	Length (L_T) min, mm
A	2.0 (±0.05)	1.5 (±0.05)	25
B	4.0 (±0.13)	3.0 (±0.13)	45
C	8.0 (±0.13)	6.0 (±0.13)	90

[A] C1161 and C1211 give complete details and graphics on parallelism, perpendicularity, chamfers, and radii.

6.3 Test specimen surfaces can be scratched or indented during handling, especially during mounting or clamping for grinding. This is most likely to occur when hard abrasive particles are present on the test specimen surface or on a surface that contacts the test specimen. An extraneous scratch or indentation can act as a source of premature failure during flexure testing. In some cases it may not be possible to distinguish between extraneous and machining induced damage.

6.4 A grinding procedure is specified in this standard for measuring a reference baseline flexure strength. Damage introduced by this grinding procedure is not expected to have a significant effect on the flexure strength of most advanced ceramic materials. For verification, fractographic examination of tested baseline-test-specimens is used to ascertain the absence of machining damage at the fracture origin. In some instances undetected grinding-induced damage may combine or join with the inherent flaw that acts as the source or origin of fracture. This may impose a negative bias on the measured flexure strength result. Residual stresses introduced by the specified grinding procedure can also influence the baseline flexure strength.

6.5 A number of flexure test related factors can influence the value of the measured flexure strength. Among the most important for susceptible materials is slow crack growth due to environmental moisture. This and other interferences are discussed in C1161 and C1211.

7. Materials

7.1 This standard covers materials that are suitable for testing by C1161 Test Method for Flexure Strength of Advanced Ceramics at Ambient Temperatures and C1211 Test Method for Flexure Strength of Advanced Ceramics at Elevated Temperatures. ASTM Standards C1161 and C1211 require that the material be isotropic and homogeneous, that the moduli of elasticity in tension and compression be identical, and that the material be linearly elastic. It is also required that the grain size be no greater than one fiftieth of the flexure test specimen thickness.

8. Test Specimen Dimensions

8.1 The required test specimen dimensions and tolerances are specified in the flexure test standards (C1161 and C1211) and are given in Table 1. In preparing test specimens, allowance must be made for a thickness ≥0.4 mm to be removed from the surface by the grinding process being tested. For most

[4] In some cases, an increase in flexure strength can be obtained by surface grinding if a highly flawed or lower-strength surface layer is removed by grinding. An increase can also result if a sufficiently large surface residual stress is introduced by grinding or if a favorable phase transformation is induced.

TABLE 2 Adjustable Machining Parameters

Wheel Speed
Down Feed
Table Speed
Cross-Feed
Grinding Direction (with respect to test specimen geometry)

TABLE 3 Grinding Wheel Characteristics

Diameter (size range determined by machine)
Width
Bond type
Grit Size
Grit Size distribution
Grit Concentration
Grit Characteristics (type, shape, friability, etc.)

materials this thickness will eliminate damage associated with prior machining operations and allow a steady state condition to be achieved for the grinding process under investigation. A thickness smaller than 0.4 mm may be used, but tests must be carried out to determine that prior damage has been removed and steady state is achieved in the grinding process under investigation. These tests will require comparison of flexure strength values obtained using the smaller thickness with values obtained for a thickness ≥0.4 mm.

9. Grinding Dimensions

9.1 A comprehensive discussion of grinding conditions is beyond the scope of this standard. More complete treatments can be found in the open literature and in textbooks on grinding (**2**). The following description is included mainly to assist in the identification and categorization of important factors. In principle, grinding conditions comprise all grinding related factors that influence the measured flexure strength of the test specimen. Some factors may be inherent to the design of the grinding machine and not easily or directly subject to control, for example, the static and dynamic stiffness characteristics of the machine, and vibrations inherent to the machine. Other factors such as the feed rates and wheel grit size are subject to direct control. This standard is primarily concerned with the evaluation of the influence of the latter factors. Grinding variables typically available for direct control are identified in the sections below.

9.2 *Directly Controlled Machining Variables*—Machining variables that are subject to direct control can be placed in three categories: (*1*) machine control parameters such as down-feed and table speed (Table 2), (*2*) grinding wheel characteristics (Table 3), and (*3*) coolant variables. As with any test, there are limits in the precision to which a given parameter can be controlled. These limits can vary substantially for different machines. For example, a conventional grinding machine with hydraulically operated table feeds probably will not offer as precise control over table speed and cross-feed as a CNC (computer numerically control) type machine with precision lead screw drives and encoder feed back. The importance of a given parameter or variable will of course depend on its influence on the flexure strength of the material being tested. Low precision with respect to a parameter or variable does not necessarily adversely affect the application of this standard. The standard can in fact be employed to assess the sensitivity of flexure strength to a given parameter or variable. For example, for a certain machine, wheel speed is reduced by 10 % under load during grinding due to limitations in motor speed control and power. The question may be asked, “Will this reduction in speed influence flexure strength?” One or more tests can be conducted at 20 % higher and lower speeds to evaluate sensitivity to wheel speed. The outcome will help determine whether, indeed, a 10 % reduction in wheel speed has a significant effect on flexure strength of the material under study.

9.2.1 Guidance in the choice of an appropriate set of grinding variables is obtained by considering the two relationships used to determine removal rate, Eq 1 and grit depth-of-cut, Eq 2. For linear reciprocating surface grinding the removal rate, Q_w, is given by:

$$Q_w = v_w a c_w \quad (1)$$

where:

v_w = table speed,
a = down-feed, and
c_w = cross-feed.

Increasing any or all of the independent variables will result in an increase in removal rate. Limits on the magnitudes of these parameters are imposed by the capacity of the machine in terms of range of operation, available power, and operating speed of the grinding wheel. The capacity of the workpiece to sustain the imposed grinding forces without failure and wheel grit size are also limiting factors. Seeking a higher removal rate by increasing v_w or a, or both, can adversely effect surface finish, flexure strength, and wheel wear.

9.2.2 The grit depth-of-cut, h_m, for linear reciprocating surface grinding can be approximated by (**2**):

$$h_m = (1/Cr)^{1/2} (v_w/v_s)^{1/2} (a/d)^{\frac{1}{4}} \quad (2)$$

where:

C = concentration per unit area of grit that are active during grinding,
r = is a factor describing the shape of the grit,
v_s = the wheel speed, and
d = the wheel diameter.

Because of variations in height and location of grit on the surface of the wheel, not all exposed grit will be engaged in cutting under a given set of grinding conditions. Those grit actually engaged in cutting are referred to as active grit. Grinding parameters should be chosen so that h_m is much less than approximately ⅓ the nominal grit size. If h_m is too large, excessive wheel wear may occur and the grinding forces may reach a level that results in complete failure of the wheel or damage to the machine or workpiece, or both. The grit depth-of-cut also plays an important role in determining grinding induced damage. It is reasoned that the greater the depth of penetration of the grit into the surface of the test specimen during material removal, the larger the cracks introduced, and consequently the greater the reduction in flexure strength. Supporting this argument is the well-known fact that cracks introduced by hardness indentation increase in size with increasing indentation force.

9.2.3 Experiments have shown that flexure strength does indeed decrease with increasing grit depth-of-cut. However, the actual relationship between flexure strength and grit depth-of-cut is quite complex and must account for the introduction of residual stresses and thermal effects, as well as dynamic material response factors and other aspects of the grit work-piece interaction process. From Eq 2, it is seen that increasing the grit concentration, wheel speed or wheel diameter decreases the grit depth-of-cut, while increasing the table speed or down-feed increases the grit depth-of-cut. The effects of down-feed and wheel diameter appear as the one-fourth root and consequently are expected to have a smaller effect relative to changes in the other parameters which exhibit a square root dependence. Although grit size does not explicitly appear in Eq 2, experiment shows that grit size is the factor that is most consistent in its influence on flexure strength. Namely, there is nearly always an inverse relationship between grit size and flexure strength. This is caused primarily by the fact the Eq 2 does not explicitly account for the non-uniform height distribution of exposed grit that exists on most grinding wheels. Thus, larger heights and correspondingly greater grit depths of penetration are almost certain to occur for larger grit sizes at a given down-feed setting.

9.2.4 *Grinding Wheel Condition (Balancing, Truing, Dressing, and Wear)*—In addition to the design characteristics of the grinding wheel (Table 3), the condition of the grinding wheel can exercise a significant influence on the damage introduced during grinding and consequently on flexure strength. The condition of the grinding wheel can be described in terms of its balance, trueness, grit exposure, and state of wear.

9.2.5 Balancing may be carried out manually by the operator, or automatically if the machine is so equipped. An out-of-balance wheel will result in vibration or oscillation of the wheel with respect to the workpiece causing the depth-of-cut to vary as the wheel rotates against the workpiece surface. The extent of these depth variations will depend on the degree of imbalance and stiffness characteristics of the machine and on grinding conditions. Out-of-balance can be detected by means of an accelerometer mounted on the grinding machine. Periodic depth waves in the surface finish topography of the workpiece may also be used to identify out-of-balance, however similar variations in surface finish may be produced by a wheel that is not true. Balancing of the wheel may be done statically or dynamically, or both, on or off the machine. Various devices and methods are available for accomplishing this.

9.2.6 A wheel that runs true is one that, when mounted on the machine, presents a grinding surface that exhibits circular symmetry with respect to the axis of rotation of the spindle. As noted above (9.2.5), a periodic variation in height (referred to as waviness) of the workpiece surface along the direction of grinding will result if the wheel does not possess circular symmetry. In reciprocating surface grinding, the wheel is generally trued to obtain a cylindrical form for generation of flat workpiece surfaces.

9.2.7 Since the waviness in the surface finish whether caused by wheel imbalance, by lack of concentricity, or by both, reflects a corresponding variation in the depth-of-cut, the potential exists for an associated adverse effect on flexure strength. Instead of a constant depth-of-cut, the actual depth-of-cut oscillates about an average value. The maximum depth-of-cut value is the relevant quantity with respect to assessing the influence of down-feed on flexure strength.

9.2.8 Because of the elastic compliance of the machine, grinding wheel, and workpiece, it should be noted that the actual depth-of-cut will be less than the set down-feed value. Only after several successive advances in down-feed will the depth-of-cut approach the set value of down-feed. In addition to elastic compliance, wheel wear also will result in a depth-of-cut that is less than the set down-feed value. Accurate determination of the depth-of-cut will require direct measurement of the thickness of material removed from the test specimen. Finally, it should be pointed out that the above influences on depth-of-cut might have only a minor effect on flexure strength because of the fourth root dependence of depth-of-cut in Eq 2.

9.2.9 Truing is normally done with the wheel mounted on the grinding machine. For diamond grit wheels, a brake truer or powered rotary truing device is commonly used. Truing with one of these devices is a grinding operation itself in which the truing device is equipped with a grinding wheel of the correct grade for the wheel being trued. Truing wheels are usually operated at a surface speed that is different from that of the wheel being trued. The ratio of grinding wheel surface speed to truing wheel surface speed is chosen to optimize the truing process, that is, to maximize the rate of volume removal from the grinding wheel and minimize the volume lost from the truing wheel. The run-out of an effectively trued wheel is typically less than 2 µm. Truing is rarely, if ever, applied to single-layer plated or brazed diamond wheels.

9.2.10 The form of the grinding wheel is also determined by truing. For planar surface grinding where the wheel periphery is the operational surface as in Fig. 2, truing is performed to make this surface cylindrical and concentric with the spindle axis of rotation. Any departure in shape from a true cylinder will cause a variation in the depth-of-cut as the wheel engages the workpiece surface. For rotary grinding modes, the face of the wheel is the primarily operational surface and truing is performed to make this surface flat and perpendicular to the spindle axis. With continued use, wheel wear will eventually determine the steady-state form of the grinding wheel. The steady state form is specific to the wheel width, grinding conditions, and workpiece dimensions.

9.2.11 Efficient cutting requires the presence of sharp grit that protrude fractionally above the surface of the surrounding bond material. Dressing refers primarily to the removal of bond material from the surface of the grinding wheel thereby increasing the height at which the grit stand above the surface, removing worn grit, or allowing the exposure of fresh grit, or combination thereof. Several methods for dressing are available. Most often dressing is accomplished by grinding a specially formulated block of material (dressing stick) composed of weakly bonded abrasive grit, commonly aluminum