Designation: C 1525 – 03

Standard Test Method for Determination of Thermal Shock Resistance for Advanced Ceramics by Water Quenching[1]

This standard is issued under the fixed designation C 1525; 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 describes the determination of the resistance of advanced ceramics to thermal shock by water quenching. The method builds on the experimental principle of rapid quenching of a test specimen at an elevated temperature in a water bath at room temperature. The effect of the thermal shock is assessed by measuring the reduction in flexural strength produced by rapid quenching of test specimens heated across a range of temperatures. For a quantitative measurement of thermal shock resistance, a critical temperature interval is determined by a reduction in the mean flexural strength of at least 30 %. The test method does not determine thermal stresses developed as a result of a steady state temperature differences within a ceramic body or of thermal expansion mismatch between joined bodies. The test method is not intended to determine the resistance of a ceramic material to repeated shocks. Since the determination of the thermal shock resistance is performed by evaluating retained strength, the method is not suitable for ceramic components; however, test specimens cut from components may be used.

1.2 The test method is intended primarily for dense monolithic ceramics, but may also be applicable to certain composites such as whisker- or particulate-reinforced ceramic matrix composites that are macroscopically homogeneous.

1.3 Values expressed in this standard test method are in accordance with the International System of Units (SI) and Standard IEEE/ASTM SI 10.

1.4 *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 and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 1145 Terminology of Advanced Ceramics[2]

C 1161 Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature[2]

C 1239 Practice for Reporting Uniaxial Strength Data and Estimating Weibull Parameters for Advanced Ceramics[2]

C 1322 Practice for Fractography and Characterization of Fracture Origins in Advanced Ceramics[2]

E 4 Practice for Force Verification of Testing Machines[3]

E 6 Terminology Relating to Methods of Mechanical Testing[3]

E 616 Terminology Relating to Fracture Testing[2]

IEEE/ASTM SI 10 Standard for Use of the International System of Units (SI): The Modern Metric System[4]

2.2 *European Standard:*

EN 820-3 Advanced Technical Ceramics—Monolithic Ceramics—Thermomechanical Properties—Part 3: Determination of Resistance to Thermal Shock by Water Quenching[5]

3. Terminology

3.1 *Definitions*—The terms described in Terminologies C 1145, E 6, and E 616 are applicable to this standard test method. Specific terms relevant to this test method are as follows:

3.1.1 *advanced ceramic, n*—a highly engineered, high performance, predominately non-metallic, inorganic, ceramic material having specific functional attributes. **C 1145**

3.1.2 *critical temperature difference, ΔT_c, n*—temperature difference between the furnace and the ambient temperature water bath that will cause a 30 % drop in the average flexural strength.

[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 Properties and Performance.

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

[3] *Annual Book of ASTM Standards*, Vol 03.01

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

[5] Available from CEN, 36, rue de Stassart, B-1050 Brussels, Belgium, www.cenorm.be.

3.1.3 *flexural strength*, σ_f, *n*—a measure of the ultimate strength of a specified beam specimen in bending determined at a given stress rate in a particular environment.

3.1.4 *fracture toughness*, *n*—a generic term for measures of resistance to extension of a crack. **E 616**

3.1.5 *slow crack growth (SCG)*, *n*—subcritical crack growth (extension) which may result from, but is not restricted to, such mechanisms as environmentally-assisted stress corrosion or diffusive crack growth.

3.1.6 *thermal shock*, *n*—a large and rapid temperature change, resulting in large temperature differences within or across a body. **C 1145**

3.1.7 *thermal shock resistance*, *n*—the capability of material to retain its mechanical properties after exposure to one or more thermal shocks.

4. Summary of Test Method

4.1 This test method indicates the ability of an advanced ceramic product to withstand the stress generated by sudden changes in temperature (thermal shock). The thermal shock resistance is measured by determining the loss of strength (as compared to as-received specimens) for ceramic test specimens quickly cooled after a thermal exposure. A series of rectangular or cylindrical test specimen sets are heated across a range of different temperatures and then quenched rapidly in a water bath. After quenching, the test specimens are tested in flexure, and the average retained flexural strength is determined for each set of specimens quenched from a given temperature. The "critical temperature difference" for thermal shock is established from the temperature difference (exposure temperature minus the water quench temperature) that produces a 30 % reduction in flexural strength compared to the average flexural strength of the as-received test specimens.

5. Significance and Use

5.1 The high temperature capabilities of advanced ceramics are a key performance benefit for many demanding engineering applications. In many of those applications, advanced ceramics will have to perform across a broad temperature range with exposure to sudden changes in temperature and heat flux. Thermal shock resistance of the ceramic material is a critical factor in determining the durability of the component under transient thermal conditions.

5.2 This test method is useful for material development, quality assurance, characterization, and assessment of durability. It has limited value for design data generation, because of the limitations of the flexural test geometry in determining fundamental tensile properties.

5.3 Appendix X1 (following EN 820-3) provides an introduction to thermal stresses, thermal shock, and critical material/geometry factors. The appendix also contains a mathematical analysis of the stresses developed by thermal expansion under steady state and transient conditions, as determined by mechanical properties, thermal characteristics, and heat transfer effects.

6. Interferences

6.1 Time-dependent phenomena such as stress corrosion or slow crack growth may influence the strength tests. This might especially be a problem if the test specimens are not properly dried before strength testing.

6.2 Surface preparation of test specimens can introduce machining flaws which may have a pronounced effect on the measured flexural strength. The surface preparation may also influence the cracking process due to the thermal shock procedure. It is especially important to consider surface conditions in comparing test specimens and components.

6.3 The results are given in terms of a temperature difference between furnace and quenching bath (ΔT). However, it is important to notice that results may be different for the same ΔT but different absolute temperatures. It is therefore specified in this test method to quench to room temperature.

6.4 The formulae presented in this test method apply strictly only to materials that do not exhibit *R*-curve behavior, but have a single-valued fracture toughness. If the test material exhibits a strong R-curve behavior, i.e., increase in fracture toughness with increasing crack length, caution must be taken in interpreting the results.

6.5 Test data for specimens of different geometries are not directly comparable because of the effect of geometry on heat transfer and stress gradients. Quantitative comparisons of thermal shock resistance for different ceramic compositions should be done with equivalent test specimen geometries.

7. Apparatus

7.1 *Test Apparatus*:

7.1.1 The test method requires a thermal exposure/quenching system (consisting of a furnace, specimen handling equipment, and a quench bath) and a testing apparatus suitable for measuring the flexural strength of the test specimens.

7.1.2 The test method requires a furnace capable of heating and maintaining a set of test specimens at the required temperature to ± 5 K (± 5°C). The temperature shall be measured with suitable thermocouples located no more than 2 mm from the midpoint of the specimen(s) in the furnace. Furnaces will usually have an open atmosphere, because air exposure is common during the transfer to the quench bath.

NOTE 1—If air exposure is detrimental, a special furnace-quench system can be set up in which both the furnace and the quench unit are contained within an inert atmosphere container. A common design for such a system consists of a tube furnace positioned vertically above the quench tank, so that the test specimen drops directly into the tank from the furnace.

7.1.3 The method requires a test specimen handling equipment designed so that the test specimen can be transferred from the furnace to the quenching bath within 5 s.

7.1.4 A water bath controlled to 293 ± 2 K (20°C ± 2°C) is required. The water bath must have sufficient volume to prevent the temperature in the bath from rising more than 5 K (5°C) after test specimen quenching. It is recommended that the bath be large enough for the test specimens to have cooled sufficiently before reaching the bottom of the bath, or contain a screen near the bottom to prevent the test specimens from resting directly on the bottom of the bath.

7.1.5 The universal test machine used for strength testing in this test method shall conform to the requirements of Practice E 4. Specimens may be loaded in any suitable test machine provided that uniform test rates, either using load-controlled or

displacement-controlled mode, can be maintained. The loads used in determining flexural strength shall be accurate within ± 1.0 % at any load within the selected load rate and load range of the test machine as defined in Practice E 4.

7.1.6 The configuration and mechanical properties of the test fixtures shall be in accordance with Test Method C 1161 for use with the standard four-point flexure specimens. If larger test pieces (sizes A or C below) are employed, the test fixture shall be scaled accordingly. There are currently no standard fixtures for testing cylindrical rods in flexure; however, the fixtures to be used shall have the appropriate articulation. Test fixtures without appropriate articulation shall not be permitted; the articulation of the fixture shall meet the requirements specified in Test Method C 1161.

7.1.7 The method requires a 393 K (120°C) drying oven to remove moisture from test specimens before (if needed) and after quench testing.

7.1.8 A micrometer with a resolution of 0.002 mm (or 0.0001 in.) or smaller should be used to measure the test piece dimensions. The micrometer shall have flat anvil faces. The micrometer shall not have a ball tip or sharp tip since these might damage the test piece if the specimen dimensions are measured prior to fracture. Alternative dimension measuring instruments may be used provided that they have a resolution of 0.002 mm (or 0.0001 in.) or finer and do no harm to the specimen.

8. Test Specimens

8.1 The ceramic test specimens shall be pieces specifically prepared for this purpose from bulk material or cut from components.

8.1.1 *Specimen Size*—Three specimen geometries are defined for use in this test method:

8.1.1.1 *Type A*—Rods 10 ± 0.13 mm in diameter, 120 mm long.

8.1.1.2 *Type B*—Bars 3 ± 0.13 mm × 4 ± 0.13 mm in cross section, minimum 45 mm long with chamfered edges, in accordance with type B in Test Method C 1161.

8.1.1.3 *Type C*—Bars 10 ± 0.13 mm × 10 ± 0.13 mm in cross section, 120 mm long, with chamfered edges.

NOTE 2—The test specimens of A and C type are intended to be large enough to produce a materials ranking that is basically independent of specimen size and appropriate for larger test specimens **(1,2)**.[6] Test specimens of B type may require greater quenching temperature differences in order to produce strength reduction. These test specimens may not correctly rank the relative behavior of larger components. Only Type B coincides with Type B in Test Method C 1161.

NOTE 3—Under some circumstances the edges of prismatic test specimens or the ends of cylindrical test specimens may be damaged by spallation during the quench test. These specimens should be discarded from the batch used for strength testing if the damage will interfere with the strength test. In any case such spallation must be noted in the report. Spallation problems can be alleviated by chamfering sharp edges.

NOTE 4—The parallelism tolerances on the four longitudinal faces are 0.015 mm for B and C and the cylindricity for A is 0.015 mm.

8.2 *Test Specimen Preparation*—Depending on the intended application of the thermal shock data, one of the four test specimen preparation methods described in Test Method C 1161 may be used: As-Fabricated, Application-Matched Machining, Customary Procedures, or Standard Procedures.

8.3 *Handling Precautions*—Care shall be exercised in storing and handling of test specimens to avoid the introduction of random and severe flaws, such as might occur if test specimens were allowed to impact or scratch each other.

8.4 *Number of Test Specimens*—A minimum of 10 specimens shall be used to determine as-received strength at room temperature. A minimum of 30 is required if estimates regarding the form of the strength distribution is to be determined (for example a Weibull modulus). A minimum of 5 specimens shall be used at each thermal shock temperature. It is recommended that as ΔT_c is established, additional 5 specimens be tested at this as well as the adjacent temperature intervals. This will allow for determination of the mean and standard deviation. If estimates regarding the form of the strength distribution at the ΔT_c and adjoining temperature intervals are desired (for example, Weibull analysis) additional specimens must be tested at these temperature intervals. See Practice C 1239 for guidance on estimating Weibull parameters.

9. Procedure

9.1 *Test Exposure Temperatures*:

9.1.1 The maximum exposure target temperature of the furnace for the thermal shock test of a given advanced ceramic will be determined from the maximum performance temperature required for a specific application, specified in a comparative thermal shock test, or cited in test literature.

9.1.2 The initial exposure temperature can be determined from literature values, prior test experience, or from a 50 % value of the maximum exposure temperature. Follow-on exposure/quench tests shall be performed such that the critical temperature difference is determined within a 50 K (50°C) interval.

9.1.3 An efficient "bracketing" search technique for ΔT_c can be employed wherein the initial exposure temperature is chosen high enough that a definitive strength drop (>30 % of as-received strength, see Fig. 1) is expected and observed. (If the strength drop is not observed, repeat the test with a higher initial temperature.) The second exposure temperature is chosen at the midpoint of the first exposure temperature and room temperature. Each subsequent exposure temperature is selected at the midpoint between the lowest temperature producing a >30 % strength drop and the highest temperature to produce a <30 % strength drop. (See Figs. 2 and 3.) Continue the iteration until the temperature interval is between iterations is less than 100°C. This search procedure minimizes the number of iterations needed to identify the ΔT_c, as compared to a stepwise fixed increment search procedure.

9.2 Clean the test specimens in water or alternate fluid to remove any cutting solutions or other contaminants. A final rinse in a quickly evaporating solvent such as acetone or ethanol is recommended. Determine the thickness and width of each test specimen in accordance with Test Method C 1161.

9.3 Dry the test specimens in an oven at 393 ± 10 K (120 ± 10°C) for 2 h. Allow the specimens to cool to room temperature in a dessicator. Select the specimens for quench testing and store in the dessicator until furnace exposure.

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

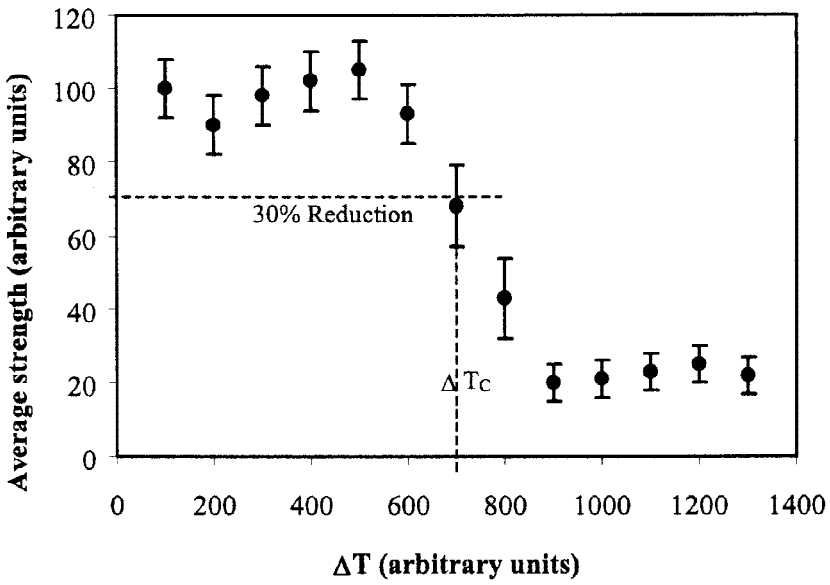

FIG. 1 Typical Plot of Average Strength Versus Quenching Temperature Difference (Not for a Specific Material)

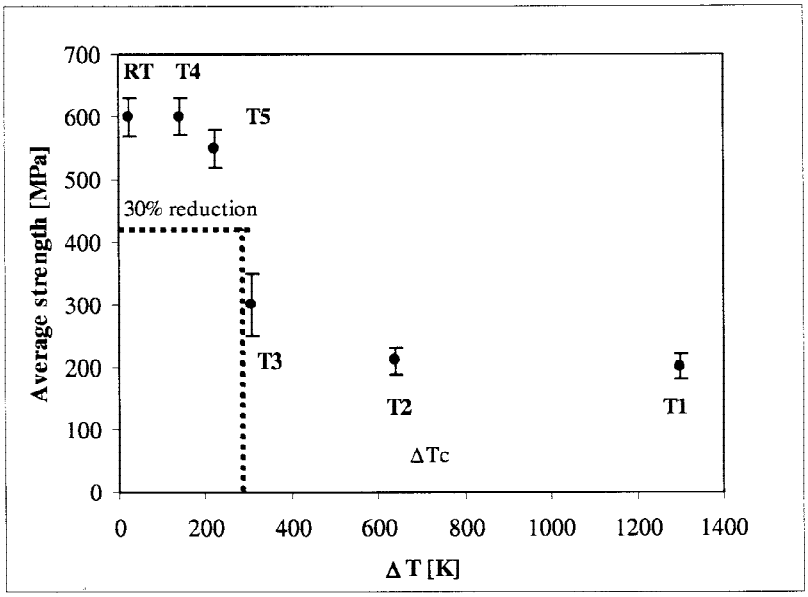

FIG. 2 Example of a Temperature Sequence Using the ″Bracketing″ Technique for a Material With a Low Thermal Shock Resistance.

9.4 Perform the initial flexural strength test on at least 10 test specimens in accordance with Test Method C 1161 using the appropriate test machine and fixture.

9.5 Determine the mean and standard deviation of the strength of the as-received specimens.

9.6 Place the first set (minimum five test specimens) of quench test specimens in the cold furnace and heat slowly [minimum 30 min to temperatures up to 873 K (600°C); minimum 60 min to temperature greater than 873 K (600°C)] to the initial exposure temperature. Equilibrate at the exposure temperature for a period of 15 min and check/record the exposure temperature. After equilibration, remove the test specimens singly from the furnace, and transfer each of them to the quench bath as quickly as possible, but in no more than 5 s. A specific orientation of the specimens during this operation is not required.

9.7 After quenching, dry the test specimens in the drying oven and store, if necessary, in a dessicator per 9.3, before strength testing at room temperature.

9.8 Conduct strength tests on the quenched and dried test specimens in flexure at room temperature in accordance with Test Method C 1161.

9.9 Calculate flexural strength according to Section 10, and compare the average flexural strength for the quenched test specimens to the strength of the as-received test specimens. A

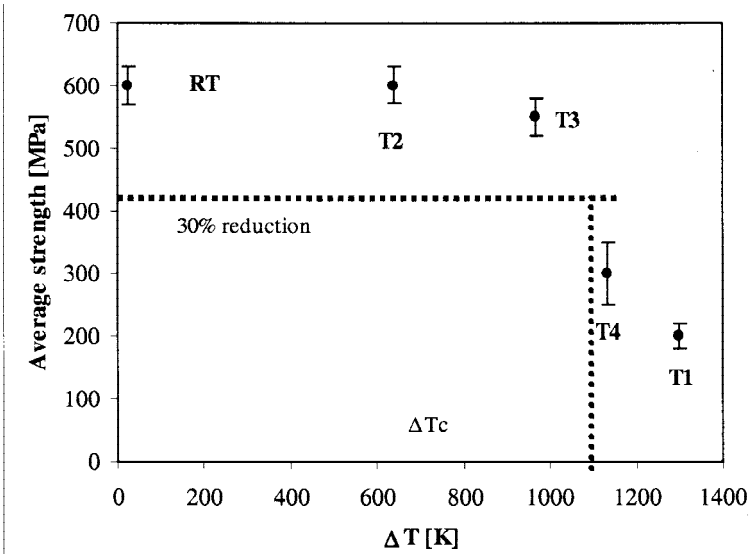

FIG. 3 Example of a Temperature Sequence Using the ″Bracketing″ Technique for a Material With a High Thermal Shock Resistance.

30 % decrease in flexural strength for a given ΔT will meet the critical ΔT requirement, see Figs. 2 and 3.

9.10 Once the exposure temperature for the ΔT is determined, repeat the test exposure/quench/strength test for the critical temperature as well as for one 50 K (50°C) temperature interval above and one below this ΔT. Calculate average flexural strength and standard deviation for the three sets of test specimens and compare those values with those obtained for the as-received test specimens. Often an increase in the standard deviation is observed for the sets tested around ΔT_c **(3)**, and this may help in determining the critical temperature interval. An example of a typical graph of average strength versus temperature interval is given in Fig. 1.

9.11 If desired, expose and test additional test sets to determine the strength reduction across the entire temperature regime of interest.

9.12 Performing fractographic analysis according to Practice C 1322 is recommended for the as-received test specimens as well as for the test specimens tested at ΔT_c. Fractography could be helpful in determining the location and source of critical fracture flaws in the as-received test specimens and assessing if thermal shock produces a change in the critical flaw population with a corresponding strength drop.

10. Calculation

10.1 Evaluate flexural strength of the prismatic test specimens according to the formula for four-point flexure (see Test Method C 1161):

$$S = \frac{3\,P(L_o - L_i)}{2b\,d^2} \tag{1}$$

where:

S = flexural strength, Pa,
P = measured fracture load, N,
L_o and L_i = outer and inner spans, respectively, m,
b = test specimen width, m, and
d = test specimen height, m.

Evaluate the strength of cylindrical test specimens as follows:

$$S = \frac{P(L_o - L_i)}{\pi\, r^3} \tag{2}$$

where:

r = radius of the test specimen cylinder.

10.2 Evaluate the mean $\bar{S}$ and standard deviation SD according to

$$\bar{S} = \frac{\sum_1^n S}{n} \tag{3}$$

$$SD = \sqrt{\frac{\sum_1^n (S - \bar{S})^2}{(n-1)}} \tag{4}$$

10.3 Calculate the ΔT for each exposure/quench test, where:

$$\Delta T = T_x - T_0 \tag{5}$$

where:

T_x = exposure test temperature, K or °C, and
T_0 = quench bath temperature, K or °C.

10.4 Plot the mean flexural strength and the standard deviations for each test set versus the ΔT, as shown in Fig. 1.

11. Report

11.1 *Test Specimens, Equipment, and Test Conditions*—Report the following information for the test specimens, equipment and test conditions. Note in the report any deviations and alterations from the procedures and requirements described in this test method.

11.1.1 Date and location of tests.

11.1.2 Geometry type and dimensions of the test specimens.

11.1.3 All relevant material data including vintage data or billet identification data. (Did all test specimens come from one billet?) If known, the date the material was manufactured should be reported.

11.1.4 Exact method of test specimen preparation, including all stages of machining.

11.1.5 Heat treatments or heat exposures, if any.

11.1.6 Relevant information on how the test specimens were randomized, if any.

11.1.7 Methods of test specimen cleaning, drying, and storage before and after quenching.

11.1.8 All preconditioning of test specimens prior to testing, if any.

11.1.9 Type, configuration and material of the test fixture.

11.1.10 Type and configuration of the data acquisition system.

11.1.11 Test temperatures and test environment (furnace temperature and quenching temperature).

11.1.12 Method of loading the test specimens into the furnace, and method of transferring the test specimens into the quenching bath.

11.1.13 Type and configuration of the testing machine including the load cell.

11.2 *Test Results*—Report the following information for the test results. Note in the report any deviations and alterations from the procedures and requirements described in this test method.

11.2.1 Number of the valid test specimens (for example, fracture in the inner load span as well as of the invalid test specimens (for example, fracture outside the inner load span) at each test rate.

11.2.2 Strength of every test specimen in units of MPa to three significant figures and corresponding exposure test temperature.

11.2.3 Mean strength and standard deviation determined for each test set at each a given exposure temperature.

11.2.4 Plot of mean strength and standard deviation versus ΔT.

11.2.5 Results from fractographic analysis if performed.

12. Precision and Bias

12.1 A precision and bias study is being planned to support the test method.

13. Keywords

13.1 ceramics; quench; strength; thermal shock

APPENDIX

(Nonmandatory Information)

X1. THERMAL STRESSES, THERMAL SHOCK, AND CRITICAL MATERIAL/GEOMETRY FACTORS

X1.1 Stresses derived from temperature gradients through the thickness of a ceramic component cannot be readily relaxed. The stresses may lead to the development of strength-degrading cracks, spallation or complete fracture. A variety of temperature gradients can cause thermal shock: sudden quenching or heating (ΔT as a function of time), steady state temperature gradients (ΔT as a function of distance), or combinations of these effects. The resulting material behavior can be very different for these different situations, and the relative importance of the factors influencing the thermal shock properties of a ceramic may be different.

X1.1.1 Important factors that influence the thermal shock resistance of ceramic components are:

X1.1.1.1 Thermal expansion characteristics; Determine the levels of thermal strains developed under the temperature gradient established in the component.

X1.1.1.2 Thermal conductivity or thermal diffusivity, or both; Affect the thermal gradients which are set up by the transfer of heat into and within the component.

X1.1.1.3 Elastic properties; Control the levels of stress developed by thermal strains.

X1.1.1.4 Geometry of the component; Control the rate of heat transfer to the component; especially wall thickness and radii of curvature of exposed corners and faces.

X1.1.1.5 Tensile and shear strength; Determine the stress level which the ceramic can withstand before tensile failure or spallation from shear stresses.

X1.1.1.6 Initial flaw distribution (density and location of crack initiating sites); Determine the tensile and shear strength in the ceramic specimen.

X1.1.1.7 Fracture toughness; Controls the resistance to propagation of cracks.

X1.1.1.8 Amount and distribution of porosity; Controls the resistance to thermal shock damage through reducing the elastic moduli.

X1.1.1.9 Surface condition (surface finish, machining damage, and emissivity); Affect the surface flaws which affect strength and change the thermal radiation heat transfer.

X1.2 The thermal gradients in a ceramic specimen or component introduce thermal strains according to:

$$\epsilon_t = \frac{\sigma_t(1-\upsilon)}{E} = \Delta T\alpha \qquad \text{(X1.1)}$$

or thermal stress:

$$\sigma_1 = \frac{\Delta T\alpha E}{(1-\upsilon)} \qquad \text{(X1.2)}$$

where:

ϵ_t = thermal strain,
σ_t = thermal stress,
E = Young's modulus,
υ = Poisson's ratio,
α = thermal expansion coefficient, and
ΔT = temperature difference (temporally or spatially).

X1.2.1 A hot ceramic specimen or component subject to sudden chilling (quenching) by complete immersion in a cooler medium will experience transient tensile stresses in the surface and comparative transient compressive stresses in the interior. Since ceramics are brittle in nature and have lower strength in tension, cracks can develop from fracture initiation sites in tension at or near the surface. Depending on the level of quenching and the properties of the material, cracking or complete failure of the component may result.

X1.2.2 A cold ceramic specimen or component subject to sudden heating by complete immersion in a hotter medium will experience the reverse situation with tensile stresses developing internally.

X1.2.3 Ceramic components subject to localized heating or chilling may experience shear stresses with spallation or flaking as a result.

X1.2.4 In order to acknowledge the importance of specimen size and heat transfer rate effects during sudden cooling or heating, Eq X1.2 is modified according to:

$$\sigma_t = \frac{\Delta T \alpha E}{(1-\upsilon)} f(\beta) \quad \text{(X1.3)}$$

where the Biot modulus β is given by:

$$\beta = \frac{a\,h}{\lambda} \quad \text{(X1.4)}$$

and

a = characteristic heat transfer length (smallest dimension or the ratio of volume to surface area),
h = surface heat transfer coefficient, and
λ = thermal conductivity.

X1.3 The Biot modulus varies with the characteristic length, the surface heat transfer coefficient and the thermal conductivity of the ceramic (see Eq X1.4). The latter two parameters vary significantly with temperature such that β may be different for similar ΔT_c that have different heating and quenching temperatures **(2-5)**. It is therefore recommended that either the tests be conducted at the same Biot modulus as expected in service, or the quench tests be performed in the regime where the results are relatively insensitive to the Biot number. Since the Biot modulus is proportional to the specimen size, this will often in practice require a larger test specimen size for thermal shock testing than would be used for mechanical tests. Caution on the selection of specimen size is warranted (see below) as the standard four-point flexure specimen (see Test Method C 1161) (3 mm thickness) renders a ΔT_c which may be too high for many ceramics **(3)**.

X1.4 To describe the relative performance of ceramic materials under thermal shock conditions, several thermal shock parameters have been employed **(6-8)**.

X1.4.1 For rapid thermal shock the thermal shock parameter of the first type is employed:

$$R = \frac{\sigma_c(1-\upsilon)}{\alpha E} \quad \text{(X1.5)}$$

Where σ_c is the critical stress needed to cause cracking or fracture. By comparing to Eq X1.2 it can be seen that R is equal to the ΔT resulting in the stress reaching a critical stress or the fracture stress. The Biot modulus can be included as follows **(1)**:

$$\Delta T_c = \frac{\sigma_c(1-\upsilon)}{\alpha E f(\beta)} \quad \text{(X1.6)}$$

Where ΔT_c is the critical temperature difference. For large values of the Biot modulus β, it is has been shown **(1)** that the critical temperature difference, ΔT_c, is equal to R, hence Eq X1.5 equals Eq X1.6.

X1.4.2 For constant rate of heat transfer between the component to the medium:

$$R' = Rk = \frac{\sigma_t(1-\upsilon)k}{\alpha E} \quad \text{(X1.7)}$$

X1.4.3 For constant rate of change of surface temperature:

$$R'' = \frac{\sigma_t(1-\upsilon)a}{\alpha E} \quad \text{(X1.8)}$$

where:

a = thermal diffusivity.

X1.4.4 For resistance to loss of strength on thermal cracking:

$$R'''' = \frac{GE}{\sigma_t^2(1-\upsilon)} \quad \text{(X1.9)}$$

where:

G = surface fracture energy.

X1.4.5 These parameters are best suited for material comparisons and must be used with caution. It is especially important that the appropriate property data over the relevant temperature range be used in the calculations. It is further important to realize that the parameters are specific to the particular heat transfer situation and to differences between crack initiation and crack propagation. For the situation in this test method, rapid thermal shock by quenching, R is most appropriate.

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