Fracture Strength

Fracture strength is one of the most commonly cited properties for structural ceramics

A number of techniques and methodologies have been developed for the measurement of fracture strength. Most of these techniques equate the fracture strength to the maximum stress (tensile or compressive) at fracture.

Consequently, in order for a particular load and specimen geometry to be useful for the determination of fracture strength, the stress distribution must be well established.

A complicating factor in the determination of fracture strength is that the strength of ceramic materials is quite sensitive to size, shape, and surface finish. This sensitivity is largely responsible for the wide variation in strength values often reported for a given material.

The primary motivation for testing materials in uniform, uniaxial stress fields is the need to control the stress-state variable to characterize the mechanical behavior of the material at given stress levels. Common methods of controlling the stress states include the application of uniaxial and uniform compressive or tensile stresses to uniformly shaped volumes of material. Use of uniaxial stress tests (tension or compression) **has been limited, especially in regard to brittle, structural ceramics,** because of the need for elaborate specimen preparation, the need for specialized testing equipment (including specimen grips), and the difficulty of achieving the necessary uniform stress state. Therefore, the flexure bar has traditionally been the popular testing arrangement for ceramics, because of the ease of fabrication of the specimen geometry, the efficient use of material, the simplicity of gripping and loading, and the seemingly straightforward analysis.

Tension

Use of ceramics at elevated temperatures in many applications has necessitated the development of methods for determining the uniaxial tensile strength of specimens uniformly stressed at both ambient and elevated temperatures. This is because in a flexure test, failure often initiates at the surface unless volume-distributed flaws are larger than the surface flaws. Direct tension strength specimens subject many more volume flaws to the maximum stress, and consequently, tensile strengths are usually lower than flexural strengths. If the design application is for a component with a large volume, then the tensile specimen data are clearly preferred since there will be less scaling of strength for size and many more volume flaws are sampled in the tension

specimen. An example of these differences is shown in **Fig. A**, which compares representative silicon nitride (PY6) tensile data to flexural data as functions of temperature. Development of the technology to perform tests to measure the ultimate tensile strength has been slowed due to problems associated with **specimen alignment**, **gripping, and design**. However, much of the difficulty associated with conducting these types of tests has been overcome, and various methods for gripping and testing have been demonstrated. Grips for holding cylindrical button-head specimens are commercially available from several vendors; but, specimen costs are still high. An example of a grip system used on round specimens is shown in Fig. B. This system is capable of reducing bending to values of less than 5% at maximum load. Similarly, grip systems for applying loads to flat specimens via pin loading have similarly been developed and are reported to suppress bending strains down to the range of 4 to 6%. Specimen design is also of concern since in brittle materials localized stress concentrations cause failure to be preferentially located in these regions giving non-representative values for the uniaxial strength. Specimen failures can also occur preferentially at stress risers where the grip makes contact.

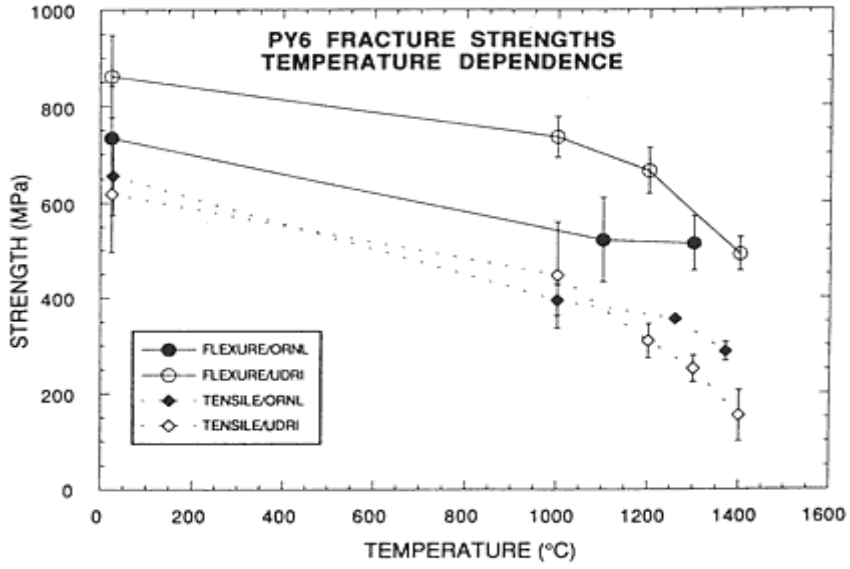


Figure A

Comparison of fracture strength of silicon nitride, PY6, obtained by flexural and uniaxial tensile bars as a function of temperature.

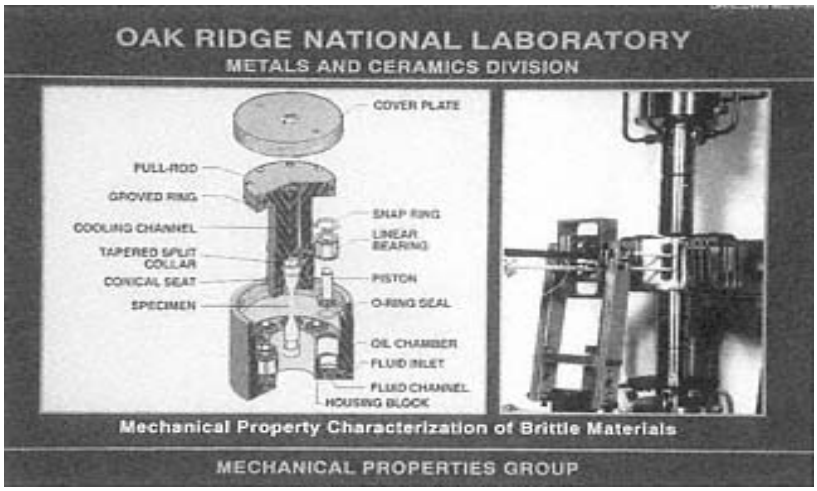


Figure B
Schematic diagram (left) of hydraulic grips used for tensile, fatigue, and creep testing of round specimens.

Figure C compares a number of tensile specimen geometries currently being used by various laboratories around the world to perform tensile tests on brittle materials. The tensile strength standard(s) for determining strength at ambient (C 1273) and elevated temperatures are applicable to monolithic and whisker reinforced ceramics.

Standard C 1275 and C 1292 specify methodology for determining the tensile and shear strength, respectively.

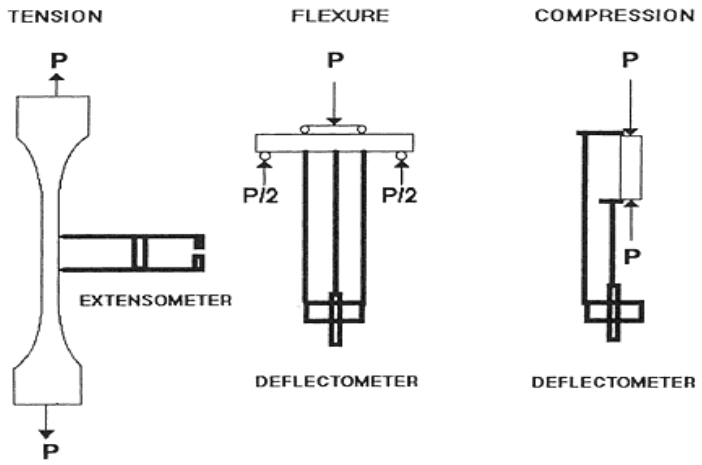


Figure
Comparison of popular specimen geometries of strength testing ceramics.

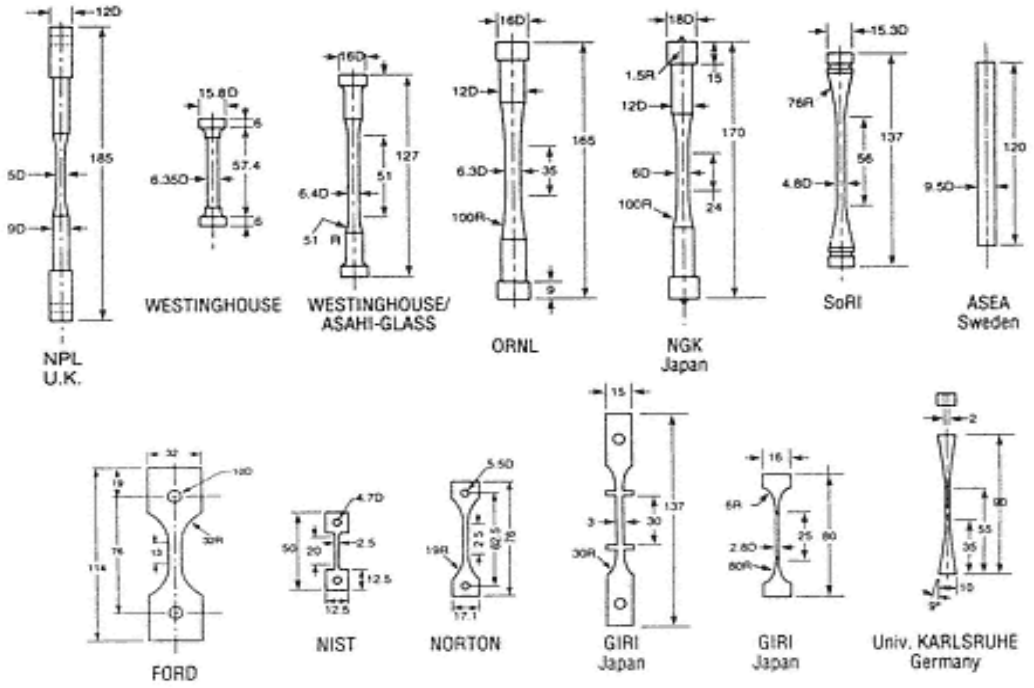


Figure C

Tensile test specimen geometries used by various laboratories.

Specimens are drawn to scale. Dimensions are in mm

Compression

The strength of ceramic materials measured in compression is much larger than that measured in tension? As a result the tensile strength is generally cited as the critical parameter for purposes of design. However, there are a number of applications including biaxially prestressed engine bearings, armor, machine tool bits, and bioceramic components for bone replacement, where the dominant loading mode is in compression. The successful utilization of ceramic components in these applications requires reliable estimates of compressive strength.

Compressive failure is thought to involve the coalescence of damage in the form of microcracks and microvoids which propagate by alternating growth and arrest mechanisms. For ceramic materials tested at ambient temperatures, this damage is thought to be generated by localized microplasticiity arising from twinning and slip. Failure occurs by structural collapse when the density of the damage zone reaches a critical size. Because this size appears to depend only upon intrinsic material characteristics, the compressive strength is generally thought to be independent of specimen size.

For the case of uniaxial testing, the compressive stress σ_c is given simply by the applied load P divided by the cross-sectional area A. However, the high stresses

required for failure under compressive loading have created a number of problems in the design of test fixtures and specimen geometries required for successful compression strength measurement. In particular, problems related to improper alignment and load block stress concentrations can lead to the generation of tensile stresses in the specimen sufficient to cause failure. Therefore, the measured compressive strength will underestimate the true value. The possible error sources are. (1) load block/specimen size mismatch, (2) load block/specimen compliance mismatch, (3) surface irregularities, and (4) eccentric loading.

RESILIENCE

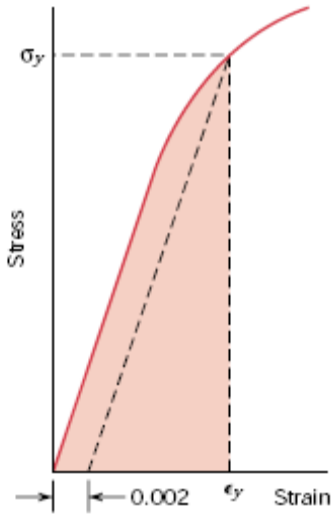
Resilience is the capacity of a material to absorb energy when it is deformed elastically and then, upon unloading, to have this energy recovered. The associated property is the modulus of resilience, Ur , which is the strain energy per unit volume required to stress a material from an unloaded state up to the point of yielding.

Computationally, the modulus of resilience for a specimen subjected to a uniaxial tension test is just the area under the engineering stress–strain curve taken to yielding

$$U_r = \int_0^{\epsilon_y} \sigma \, d\epsilon$$

Assuming a linear elastic region,

$$U_r = \tfrac{1}{2}\sigma_y \epsilon_y$$



in which ε_y is the strain at yielding.

The units of resilience are the product of the units from each of the two axes of the stress–strain plot. For SI units, this is joules per cubic meter (J/m3, equivalent to Pa)

$$U_r = \tfrac{1}{2}\sigma_y \epsilon_y = \tfrac{1}{2}\sigma_y \left(\frac{\sigma_y}{E}\right) = \frac{\sigma_y^2}{2E}$$

Thus, resilient materials are those having high yield strengths and low moduli of elasticity; such alloys would be used in spring applications.

TRUE STRESS AND STRAIN

The cross-sectional area is decreasing rapidly within the neck region, where deformation is occurring. This results in a reduction in the load-bearing capacity of the specimen. The stress, as computed from Equation 7.1, is on the basis of the original crosssectional area before any deformation, and does not take into account this diminution in area at the neck.

Sometimes it is more meaningful to use a true stress–true strain scheme. True stress σ_T is defined as the load F divided by the instantaneous cross-sectional area Ai over which deformation is occurring (i.e., the neck, past the tensile point), or

$$\sigma_T = \frac{F}{A_i}$$

Furthermore, it is occasionally more convenient to represent strain as true strain ε_T, defined by

$$\epsilon_T = \ln \frac{l_i}{l_0}$$

If no volume change occurs during deformation, that is, if

$$\mathbf{A_i l_i \_ A_0 l_0}$$

true and engineering stress and strain are related according to

$$\sigma_T = \sigma(1 + \epsilon)$$

$$\epsilon_T = \ln(1 + \epsilon)$$

Ex:- A cylindrical specimen having an original diameter of 12.8 mm (0.505 in.) is tensile tested to fracture and found to have an engineering fracture strength _f of 460 MPa (67,000 psi). If its cross-sectional diameter at fracture is 10.7 mm (0.422 in.), determine:

(a) The ductility in terms of percent reduction in area. 30%

(b) The true stress at fracture. 660 MPa

Factors effect on ceramic strength

1- Processing and Surface Flaws

The flaws in ceramics can be either internal or surface flaws generated during processing or surface flaws introduced later, during machining or service.

Pores

Pores are usually quite deleterious to the strength of ceramics not only because they reduce the cross-sectional area over which the load is applied, but more importantly because they act as stress concentrators. Typically the strength and porosity have been related by the following empirical relationship:

$$\sigma_p = \sigma_0 e^{-BP}$$

where P, σ_p, and σ_0 are, respectively, the volume fraction porosity and the strength of the specimen with and without porosity; B is a constant that depends on the distribution and morphology of the pores.

Inclusions

Impurities in the starting powders can react with the matrix and form inclusions that can have different mechanical and thermal properties from the original matrix. Consequently, as a result of the mismatch in the thermal expansion coefficients of the matrix am and the inclusions ah large residual stresses can develop as the part is cooled from the processing temperature.

Agglomerates and large grains

The rapid densification of regions containing fine particles (agglomerates) can induce stresses within the surrounding compact. Voids and cracks usually tend to form around agglomerates. These voids form as a result of the rapid and large differential shrinkage of the agglomerates during the early stages of sintering. Since these agglomerates form during the fabrication of the green bodies, care must be taken at that stage to avoid them.

Surface flaws

Surface flaws can be introduced in a ceramic as a result of high-temperature grain boundary grooving, postfabrication machining operations, or accidental damage to the surface during use, among others. During grinding, polishing, or machining, the grinding particles act as indenters that introduce flaws into the surface. These cracks can propagate through a grain along cleavage planes or along the grain boundaries, as shown in Fig. D.

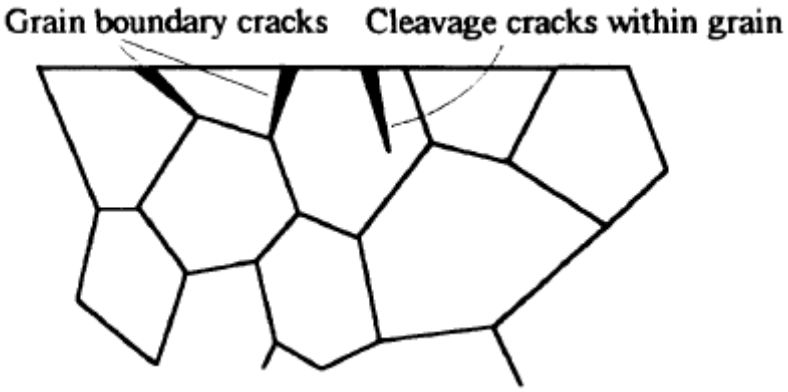


Figure D Schematic of cleavage and grain boundary cracks that can form on the surface of ceramics as a result of machining. The flaws are usually limited to one grain diameter, however, because they are deflected at the grain boundaries.

2- Effect of Grain Size on Strength

Typically, the strength of ceramics shows an inverse correlation to the average grain size G. A schematic of the dependence is shown in Fig. E, where the fracture strength is plotted versus $G^{-1/2}$.

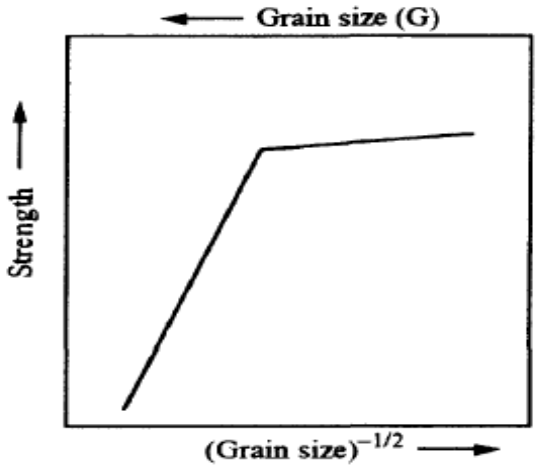


Figure ESchematic relationship between grain size and strength for a number of ceramics,

3- Effect of Compressive Surface Residual Stresses

The introduction of surface compressive layers can strengthen ceramics and is a well-established technique for glasses. The underlying principle is to introduce a state of compressive surface residual stress, the presence of which would inhibit failure from surface flaws since these compressive stresses would have to be overcome before a surface crack could propagate. These compressive stresses have also been shown to enhance thermal shock resistance and contact damage resistance.

4- Effect of Temperature on Strength

The effect of temperature on the strength of ceramics depends on many factors, the most important of which is whether the atmosphere in which the testing is being carried out heals or exacerbates preexisting surface flaws in the material. In general, when a ceramic is exposed to a corrosive atmosphere at elevated temperatures, one of two scenarios is possible: (1) A protective, usually oxide, layer forms on the surface, which tends to blunt and partially heal preexisting flaws and can result in an increase in the strength. (2) The atmosphere attacks the surface, either forming pits on the surface or simply etching the surface away at selective areas; in either case, a drop in strength is observed. For ceramics containing glassy grain boundary phases, at high enough temperatures the drop in strength is usually related to the softening of these phases.

Example problem: In a tensile test, a material fractured before necking. The true stress and strain at fracture were 630 MPa and 0.18 respectively. What is the tensile strength of the material?

SOLUTION: The engineering strain at fracture was

e =exp(0.18)−1=0.197. Because

$s = \sigma/(1 + e)$, the tensile strength=630/1.197=526 MPa.

Example problem: When the porosity of a certain ceramic is reduced from 2.3% to 0.5% the fracture stress drops by 12%. Assuming Equation (19.8), how much would the fracture stress increase above the level for 1/2% porosity if all porosity were removed?

SOLUTION:

$\sigma_2/\sigma_1 = \exp(-bP_2)/\exp(-bP_1)$

$= \exp[b(P_1 - P_2)]$, $b = \ln(\sigma_2/\sigma_1)/(P_1 - P_2)$. Substituting $\sigma 2/\sigma 1 = 1/0.88$

and $P_1 - P_2 = 0.023 - 0.005 = 0.018$,

$b = \ln(1/0.88)/0.018 = 7.1$.

$\sigma 3/\sigma 2 = \exp[-b(P_3 - P_2)] = \exp[-7.1(0 - 0.005)]) = 1.036$ or a 3.6% increase.