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Journal of the European Ceramic Society 34 (2014) 3435–3460

www.elsevier.com/locate/jeurceramsoc

Feature Article

# On the relationship between ceramic strength and the requirements for mechanical design

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Received 30 October 2013; received in revised form 31 March 2014; accepted 12 April 2014
Available online 23 June 2014

**Abstract**

During the last fifty years the mechanical properties of ceramic materials have been greatly improved, their toughness and strength have been increased and the scatter of strength decreased. Adequate statistical design procedures for brittle materials exist but cracking and brittle fracture of ceramic components still occur very often.

In this review the theory of brittle fracture and the underlying assumptions are critically discussed and the measurement procedures of strength are reviewed. It is shown that the strength of materials, the strength of specimens and the strength of components are often quite different properties. Three main factors are identified which – in order to avoid unexpected failure of components – have to be considered much more than in the past: (i) hidden stresses, i.e. stresses caused by thermal strain mismatch, by contact (for example in joints) and internal stresses, (ii) the quality of the component's surfaces and edges and (iii) proper handling of ceramic materials and components.

It can clearly be stated that the mechanical properties of many ceramic materials are appropriate even for applications under severe loading conditions but bad or incomplete mechanical design, insufficient surface finish and mishandling are the main reasons for unexpected failure of ceramic components.


*Keywords:* Mechanical reliability; Strength; Brittle fracture; Fracture statistics; Tensile stresses

## 1. Introduction

Ceramics are brittle materials, and cracking and brittle failure are serious problems during production and in service. Indeed, the brittle behaviour of ceramics builds the highest barrier against their much wider use (compared to today), in structural as well as in functional applications. To give only a few examples of the author's personal experience in this field, within recent years he has worked on cases of brittle failure of gas turbine rotors (Fig. 1a),[1] valves,[2–5] tools for cold and hot metal working,[6–10] bearings,[11] hip joints (Fig. 1b),[12–14] varistors,[15–22] thermistors (Fig. 1c),[17,19–21,23–26] LTCCs[27–29] and electrolytes in SOFCs.[30] He has even dealt with cracks in and brittle failure of semiconductor chips.[31,32] It is interesting to note that brittle failure of functional ceramic components is much more frequent than that of structural ceramic components (since there exist many more functional than structural ceramic components).[33,34]

A strategy against brittle failure of materials is improving mechanical properties, especially toughness and strength.[35–39] Several toughening mechanisms for ceramics have been identified. The main types are process zone[40–49] and bridging mechanisms.[44,50–57] The toughness levels of several structural ceramics have been significantly increased[58] and fracture toughness values of commercial materials can now reach that of cast iron (5–20 MPa $\sqrt{m}$). To give some examples[b] published

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[b] Fracture toughness testing of brittle materials is very demanding and measurements made by different laboratories may give very different results. Process- and bridging zones need some crack advance to develop and therefore the fracture toughness increases with the crack growth (*R*-curve behaviour). Different methods tend to determine toughness at different points on the *R*-curve.

http://dx.doi.org/10.1016/j.jeurceramsoc.2014.04.026
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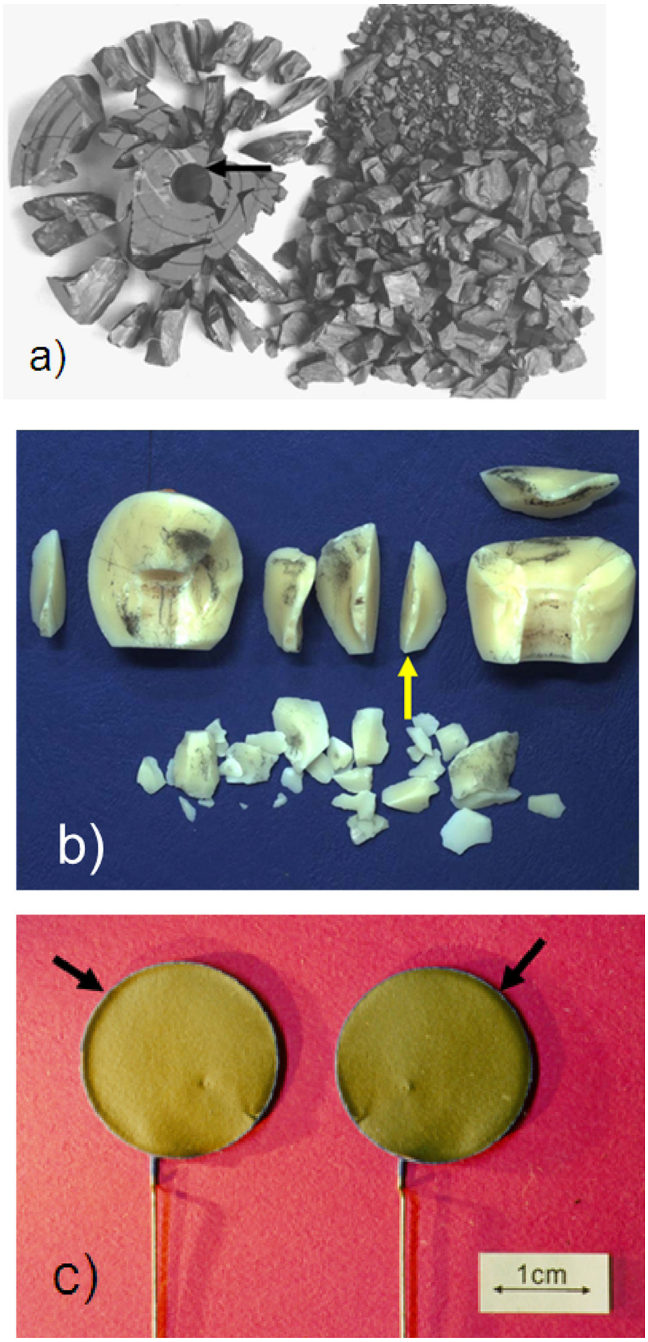


Fig. 1. Brittle failure of ceramic components. Fracture origins are highlighted by arrows. Fracture origins are shown in inserts. (a) Ceramic gas turbine rotor fractured in a cold spin (by courtesy of K.D. Mörgenthaler).[1] (b) Ceramic hip joint fractured in vivo (by courtesy of Elsevier).[14] (c) Ceramic thermistor fractured in an electrical test (by courtesy of Elsevier).[24]

toughness values are: alumina up to 5 MPa $\sqrt{m}$,[59,66] silicon nitride up to 10 MPa $\sqrt{m}$,[67] zirconia up to 7 MPa $\sqrt{m}$[68] or diamond based materials up to 11 MPa $\sqrt{m}$.[69] It is interesting to note that almost no work on toughening of functional ceramics is reported although brittle failure of functional ceramic components is a serious problem.

The strength of many materials has also been increased significantly.[58] For example the strength of some commercial materials are claimed even to reach the strength of high alloyed steels (alumina up to 630 MPa,[70] silicon nitride up to 1400 MPa,[71] zirconia more than 1600 MPa[72,73] or diamond based materials up to several thousand MPa[74]). But brittle failure of ceramic components still is a frequent problem. This causes some important questions:

- Can we measure mechanical properties of ceramics properly?
- Are we measuring the relevant properties?
- Are our design procedures appropriate for ceramic components?
- What does the tensile strength of ceramic materials mean?

In ceramic materials brittle fracture starts at flaws (the fracture origins), which are distributed throughout the material.[36–39,75] Flaws are inhomogeneities in the microstructure. Within the framework of linear elastic fracture mechanics, these inhomogeneities are typically described as cracks. Cracks propagate if the energy released by the crack propagation overcomes the energy necessary to create new fracture surfaces.[35–38,76–78] Based on this idea the Griffith/Irwin fracture criterion has been developed. Brittle failure occurs (i.e. a crack propagates in an unstable manner) if the stress intensity factor ($K = \sigma Y \sqrt{\pi a}$) of the critical crack (the critical flaw) reaches or exceeds a critical value (the fracture toughness $K_c$)[79,80]:

$$K \geq K_c. \tag{1}$$

The tensile stress $\sigma$ acts perpendicular to the crack faces (mode I loading) and pulls them apart. $a$ is the crack length and $Y$ a geometric factor, which depends on the geometry of crack, specimen and stress field and of the length of the crack. For cracks which are very small compared to the specimen size and for homogeneous tensile loading the geometric factor is about unity. For a very small penny shaped volume crack it is $2/\pi$ and for a very small straight through edge crack, it is 1.12.

At the moment of failure rearranging Eq. (1) gives an equation for the tensile strength[35,37,38,76,78]:

$$\sigma_f = \frac{K_c}{Y\sqrt{\pi a_c}}, \tag{2}$$

where $a_c$ is the length of the critical crack (the Griffith crack length; it is the smallest dimension of a crack causing brittle fracture). The tensile strength increases with the fracture toughness and is inversely proportional to the square root of the critical crack length. Rearranging Eq. (2) gives an expression for the Griffith crack length[33,38]:

$$a_c = \frac{1}{\pi} \cdot \left(\frac{K_c}{Y\sigma_f}\right)^2. \tag{3}$$

At a low applied stress only large flaws may become critical but with increasing stress even smaller flaws may become critical.

The test results also depend on the length of the starter cracks. The numbers indicated here give an indication of an upward trend with material development. Although these aspects would require a longer discussion they are outside the scope of this paper. Good summaries can be found in the literature.[59–65]