

OVERVIEW OF RELIABILITY IN STRUCTURAL CERAMICS

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ABSTRACT

The failure prediction requirements and the pertinent accept/reject criteria for structural ceramics are derived, and the available failure prediction techniques are examined, vis-a-vis the failure prediction relations, in order to highlight the capabilities and limitations of each technique. The need for additional techniques is thereby demonstrated. The capabilities of the ultrasonic technique are extensively evaluated in order to determine its ability to satisfy the deficiencies in the existing failure prediction repertoire. The prospects are shown to be very encouraging, but the results of several key studies must be awaited before defining the ultimate role of ultrasonic failure prediction techniques.

I don't intend to emphasize particular failure prediction techniques--that is the intent of the Poster Session and the subsequent talks--but I wish to indicate at the outset that there are several ways of predicting failure in ceramics. It is convenient to separate these into two groups. One group consists of direct techniques, where the defect is detected directly and the fracture mechanics analysis is applied to the defect to predict failure; these include, ultrasonics, micro-focus x-radiography, microwaves (see Poster Session) and, of course, dye penetrants. The other group consists of indirect techniques that are particularly pertinent to ceramics. These include overload proof testing (see Poster Session), flaw statistics, and intriguingly, ultrasonic attenuation.

In attempting quantitative failure prediction, we recognize that the defects are irregular in shape and that the defect size range of concern is 10 to 100 microns. What defect features need to be characterized to enable us to predict failure effectively? The first parameter is the defect size, especially the maximum dimension of that defect. The realization that the size distribution of defects in most materials generally has an extreme value form can also be used to good effect. The second defect characteristic is its orientation; normally, in ceramics, the distribution of orientations is essentially random. The third parameter is the aspect ratio of the defect; for which a normal distribution seems reasonable. The fourth feature of great importance, perhaps even more important than the aspect ratio and the orientation, concerns the physical properties of that defect, e.g., the elastic properties, and the thermal expansion coefficient.

The sequence involved in predicting failure is in three parts: firstly, we would like to characterize the defect, then the crack evolution from the defect, and finally, the slow crack growth.

I shall describe an approach based on a fairly quantitative inspection technique and a more qualitative technique. Starting with a series of samples or actual components containing defects of known size and geometry, we can relate the actual defect size to the interpreted defect size through a specific model and signal analysis procedure (Fig. 1). Of course, this isn't just a line through the origin; because, for different

types of defect the inferred size can be different for a specified actual size. Also, there is a lower limit for each type of defect and inspection technique.

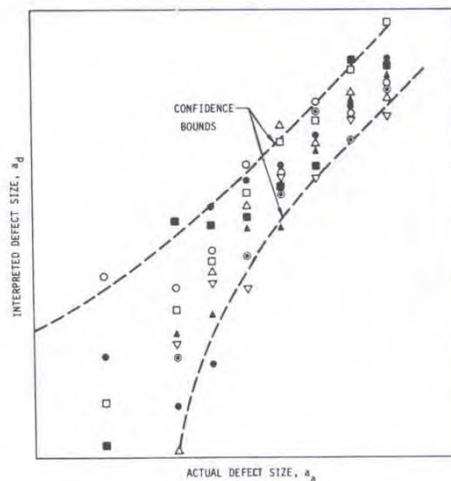


Figure 1. A plot illustrating a probable relation between the actual and detected defect sizes for a quantitative ultrasonic flaw detection method.

For a more typical technique (e.g., micro-focus x-rays or a conventional ultrasonic method), certain types of defects will never be detected, regardless of their size, and there is a wide range of inferred defect sizes (Fig. 2). For illustration, some data obtained on a silicon nitride material, containing several types of defect, using high frequency ultrasonics and using microfocus x-radiography, are summarized in Table I.

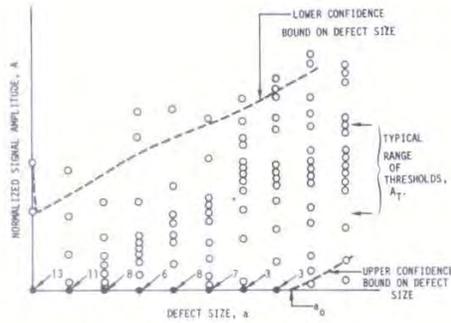


Figure 2. A typical test sequence relating the ultrasonic signal amplitude to the actual defect size. The sequence involves taking samples containing defects of the same size, but of different type (i.e., voids and various inclusions) and measuring the signal intensity from each defect. This process is repeated for a range of defect sizes.

	INTRINSIC DEFECT	DEFECT + APPLIED STRESS	EQUIVALENT SHARP CRACK
INCLUSIONS	1. HIGH $E_i \approx E_0$		
	2. SIMILAR $E_i \approx E_0$		
	3. SMALLER $E_i < E_0$		
	4. CHEMICALLY DEGRADED MATRIX		
PORES	1. FINE GRAINED MATRIX		
	2. COARSE GRAINED MATRIX		

Figure 3. A schematic indicating the relative severities of typical defects in structural ceramic matrices.

Table I. Experimental and Theoretical Scattering from Boron Nitride Defects in Silicon Nitride

Diameter	Experimental Return Signal Amplitude	Theoretical Return Signal Amplitude
500 μm	-18.4 dB	$-19.8 + 10 \log_{10} r^2$
250 μm	-26.7 dB	$-25.8 + 10 \log_{10} r^2$
125 μm	-30.8 dB	$-31.8 + 10 \log_{10} r^2$
25 μm	-36.0 dB	$-45.8 + 10 \log_{10} r^2$

For the second aspect of the failure prediction, cracks will not evolve from all defects of a given size at the same stress level (Fig. 3). The equivalent size of a sharp crack depends upon the type of defect relative to the properties of the matrix. If the elastic properties of the inclusion are similar to the matrix, there would be no stress concentrations and the defect is relatively innocuous, especially if its thermal expansion coefficient is similar to that of the matrix (so that no stresses will develop during cooling from the fabrication temperature). However, when both the elastic modulus and the thermal expansion coefficient of the inclusion are lower than that of the matrix, the equivalent crack size can be many times the inclusion size. It isn't clear how the expansion coefficient can be deduced non-destructively, but hopefully, it might be inferred from the acoustic impedance for a limited set of possibilities.

Because of the characteristics summarized in Fig. 3, when a sample is stressed to failure, e.g., at a constant stressing rate, then for a given defect size the fracture stress would not be a unique quantity (Fig. 4).

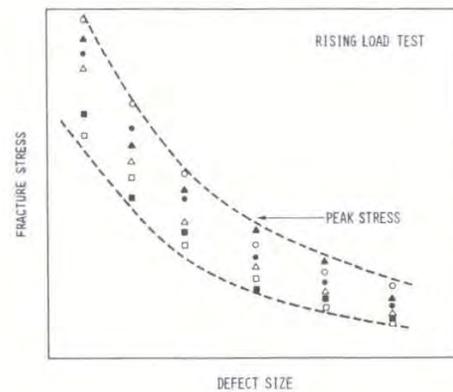


Figure 4. A typical variation of the fracture stress with defect size and type.

If probabilities are now assigned to the interpreted defect size $P(a_j)$ and the fracture strength $P(\sigma_j)$, these probabilities can be combined to obtain the probabilities of fracture that correspond to each interpreted defect size (Fig. 5). Then, by combining with some a priori distribution of defect sizes, we can also derive the rejection probability for satisfactory parts (Fig. 5). What does this mean? It means that if the application specifies that only a certain proportion of components are allowed to fail in-service (the maximum allowable failure probability) there is a corresponding interpreted defect size, and rejection probability (Fig. 5). If the inspection technique is not very quantitative, many components which really would have performed quite well in-service would be rejected (Fig. 5), and that may be economically intolerable. However, for a more quantitative inspection technique, it is evident from Fig. 5 that the rejection probability can be substantially reduced into the realm of economic viability.

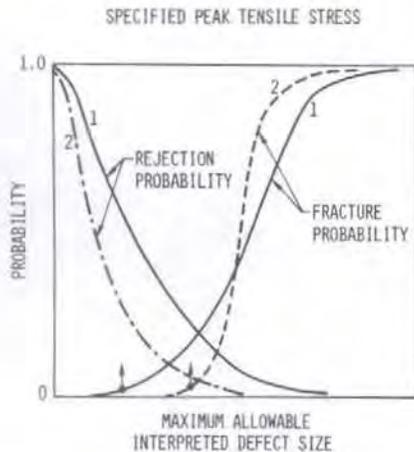


Figure 5. Fracture and rejection probabilities as a function of integrated defect size for two inspection techniques; 2 is superior to 1.

The third aspect of predicting failure, which I haven't described in detail because it's relatively well understood, concerns the slow crack growth.

I shall conclude by quickly describing a few indirect techniques. Certain ceramics, because of either a coarse grain structure, or porosity, are not amenable to high frequency ultrasonic inspection because their attenuation is too large. What do we do then to characterize small defects? It's a real problem. But one possibility, which is rather intriguing, is the use of acoustic attenuation. We have developed a theory of acoustic attenuation based on extreme value statistics, wherein only the largest grains (pores) are considered to contribute significantly to the attenua-

tion. We also know that the large size extreme of voids in porous materials, or grains in large grained materials, are the fracture origins (see Poster Session). So, because both the attenuation and fracture are related to the extremes of the microstructure, there is a potential that by measuring the frequency dependence of the attenuation we should be able to infer the actual fracture strength (or the fracture probability) of that component (Figs. 6 and 7).

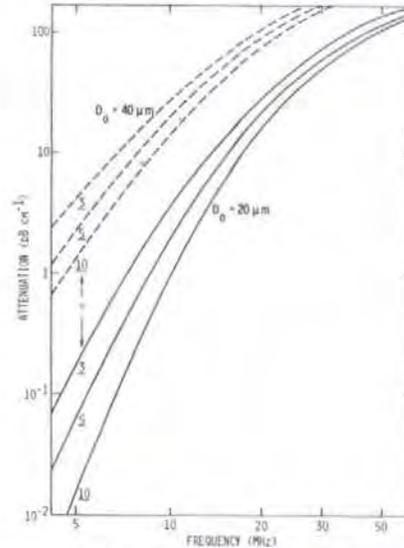


Figure 6. The prediction variation of attenuation with frequency for two grain size distributions.

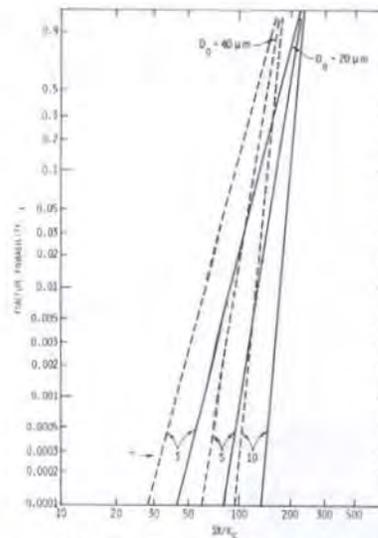


Figure 7. The predicted relation between fracture probability ϕ and strengths for two grain size distributions.

The statistical method has been traditionally used for predicting failure in ceramics. The method is as follows. You can measure the strength of, say, 50 or 100 or 1000 ceramic bars and find the probability of fracture as a function of strength, using order statistics. This probability of fracture is related both to the basic distribution of flaw strengths (of the distribution of flaw sizes) and to the volume of the part. Very recently, techniques for deriving the flaw strength distribution have been devised, and we feel quite comfortable now about this aspect of the process. However, there are still problems associated with failure prediction. Firstly, we find that there are usually several populations of flaws; for example, in bend test, fracture typically occurs from surface cracks produced by machining, giving one population. But in tensile tests, internal defects (inclusions and voids) offer control fracture, giving another population with a lower strength level. So to characterize the flaw population at the strength level that the components will experience, very expensive tensile tests will be required, and it very quickly becomes economically intractable because of the large number of experiments involved. The other problem is that on a batch-to-batch basis the populations can change. Every batch of material will thus have to be re-characterized.

In conclusion, there are a number of techniques available for detecting defects in ceramics; but it is not sufficient to detect defects, we must also characterize their size and infer something about the properties of that defect. The most effective technique for this purpose could be material specific and component specific.

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