FRACTURE MECHANICS, SUB-CRITICAL EVENTS AND STRUCTUE OF POLYPHASE CERAMICS

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ABSTRACT

A discussion of mechanical, acoustic and microstructural observations on ceramic systems of varying amounts of hetereogeneity, on the basis of mechanisms of failure, is presented. The form of the failure is observed to change as the scale of the inhomogeneity increases, so that for materials containing microstructural features of size larger than ∿ 100μm acoustic emission studies give evidence of the occurrence of numerous sub-critical events. These changes are used to consider the validity of assumptions used in fracture mechanics applied to coarsely grained materials.

KEYWORDS

Polycrystalline ceramics, strength, fracture mechanics, sub-critical events, acoustic emission, heterogeneous structures.

INTRODUCTION

It has been recognised for many years that the stronger, more uniformly structured ceramics behave differently to weaker, coarse structured materials. Acoustic emission has given further confirmation that the *form* as well as the extent of the behavioural differences of bodies to external loads changes.

The problem that this paper addresses is that of the scale of response of materials. When one considers the behaviour of a polycrystalline ceramic and its relation to the properties of the individual phases, the extent, quantitatively, of the differences must be considered. A single crystal may or may not show plastic deformation, but, because of this structure, polycrystalline ceramics are brittle. Further, brittle behaviour itself is not structurally independent.

FRACTURE OF CERAMICS

If we consider tests of fracture properties of ceramics such as the strength (i.e. load to failure) and toughness (i.e. resistance to crack propagation) there is no immediately apparent reason why the establishment of the size of the flaw that propagated (the 'critical' Griffith flaw) should not connect these as usually and, more particularly, why a sub-critical flaw should cease to propagate after initially moving (this discussion does not consider the different situation of sub-critical growth of cracks in a chemically active environment). It is, however, clear that in *coarse* structured, many fracture events can and do occur at loads very much below the critical. At some level of scale of structure, the sample itself becomes an extension of the loading machine and fracture occurs in a part of the structure and not as a catastrophic failure of the sample as a whole.

In a recent paper (Davidge, 1980) it is pointed out that the highly successful combinations of fracture mechanics and probabilistic techniques for evaluating the maximum working strength of a ceramic are largely empirical. He goes on to discuss the links between microstructure, fracture mechanics and statistical effects and his analysis will be used as the framework for the discussion in this paper of our own results which have been reported in detail elsewhere (Alderson 1977, Al-Hathlol 1980).

In the usual fracture mechanics approach

$$\sigma_f \propto \left(\frac{E\gamma_i}{C}\right)^{\frac{1}{2}} = \frac{K_{IC}}{C^{\frac{1}{2}}} \qquad (1)$$

where γ_i is the effective surface energy and K_{IC} the fracture toughness. Davidge, 1980 points out that the fracture may be preceded by a period of sub-critical growth because the requirement of energy for a crack of the same dimensions as the grain size will approximate to the cleavage or grain boundary surface energies which are much less than γ_i. Thus the increase of surface energy to propagate a crack beyond a grain may occur over a few grain dimensions.

K_{IC} measurements from large cracks introduced into specimens mean that the cracks are sampling a statistically large part of the sample as it propagates. Our results on fired clays of a wide range of structures (Alderson, 1977) confirm the generally small variation even though there is clear evidence for very marked sub-critical activity (Al-Hathlol, 1980).

When considering the flaw size variations, the situation is far easier to analyse in simple microstructures. Here it is also now possible to predict, from geometrical models (McClintock and Zaverl , 1979) or from a distribution of microcracks around a crack tip (Hoagland and Embury , 1980), that flaws can grow by several grain diameters before catastrophic failure.

Thus there are grounds for accepting sub-critical events occurring in brittle polycrystalline materials both on energetic and strength controlling grounds. However, there are a number of features of the results we have obtained that present difficulties when applying these approached to the much more complicated structures we have examined.

SUMMARY OF EXPERIMENTAL DATA

Table 1 presents a very brief summary of our data with particular reference to acoustic emission. The highly uniform structures of high strength have a fine microstructure (Plate 1) and show very little acoustic emission activity before failure. Similarly, singly phased materials such as glass and quartz single crystals show no acoustic activity. We may therefore conclude that for such materials, propagation of a single critical flaw, combined with relatively few microcracks in the process zone (cf. the discussion above), at high loads determines the failure.

However, when the results for the coarse structured clay based ceramics and refractories (e.g. Plate 2) are considered, it is clear that the situation is very different. Here we see acoustic activity at low loads and large numbers of events occurring well before failure. These are associated with fracture of

TABLE 1

STRUCTURE & MECHANICAL PROPERTIES

Material	Structure		Strength	Young's Modulus	Acoustic Emission		
	Phases	Max particle size µm	MNm^{-2}	GNm^{-2}	Onset % failure load	Extent	Amplitude Distribution range
Glass (soda-lime)	1	sample	69	70	100	1 burst	full
Quartz	1	single crystal	-	-	100	1 burst	full
SiC (refel)	2	20	525	413	95	2 bursts	wide
Al_2O_3(95%TD)	1	30	290	250	100	1 burst	wide
Kaolin (fired 1250°C)	3	50	28	28	30	several bursts	low range
Kaolin & feldspar (fired 1250°C)	4	75	48	45	40	several bursts	low range
Graphite	1	10^3	10	20	30	continuous	low-medium
Chrome-mag refractory	many	5×10^3	5	8	<30	many bursts	low-range
Electrical porcelain	4+	50µm	70	90	>60%	few bursts	medium-high

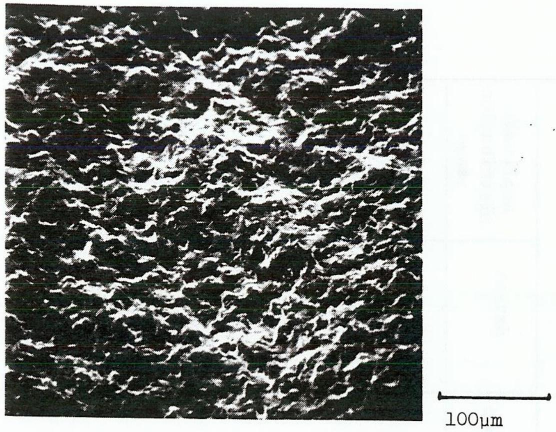

Plate 1. Fracture Surface of Refel Silicon Carbide

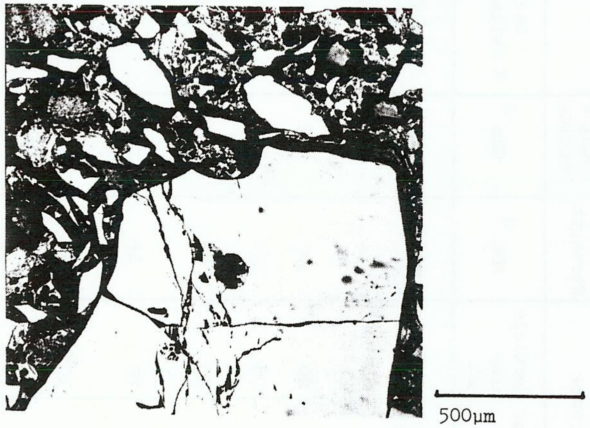

Plate 2. Polished Section of Chrom-Mag Refractory

small areas of the structure. At the same time the hetereogeneity of the systems is increasing and the overall load bearing capacity is reduced.

Tests were performed on electrical porcelains which were selected as being materials of intermediate strength and structural scale. These materials showed similarly intermediate acoustic activity patterns.

The range and magnitude of the acoustic emission amplitudes also varies consistently with structural change Figure 1.

FAILURE OF HETEROGENEOUS CERAMICS

The difficulties of identifying flaw size and surface energy just discussed are obviously further exaggerated in these materials. However, as the heterogeneity increases, a further, more fundamental, problem also becomes significant. This is

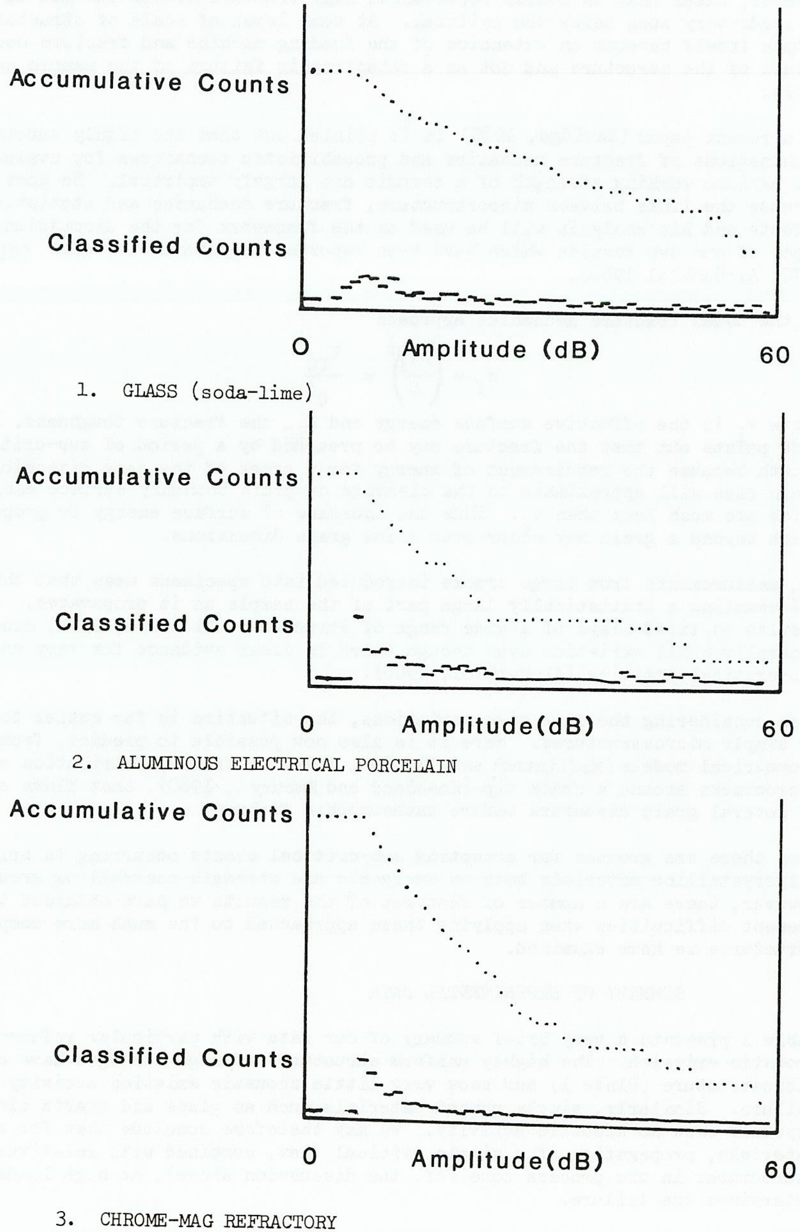

FIGURE 1. ACOUSTIC EMISSION AMPLITUDE DISTRIBUTIONS (Data from Cox & Cooke, 1980).

that in all the calculations in linear elastic fracture mechanics, the load is assumed to be transmitted to the crack tip by a more or less uniform elastic field whose properties are given by the bulk elastic moduli. Clearly, the transmission of load to various components of heterogeneous structures is not a linearly elastic effect.

On the other hand, it is striking that the ratio of average strength to bulk elastic modulus, ε_c, called by Astbury 1963 the critical strain, lies within a very limited range around 1 millistrain, for *all* ceramic materials. If we rewrite the Griffith condition in terms of this i.e.

$$c = \frac{E\gamma_i}{4\sigma^2_f} = \frac{\gamma_i}{4E\varepsilon^2_c} \qquad (2)$$

and so, on substituting appropriate values for fired clay (Alderson 1977), for example, the nominal critical flaw size can be calculated as $\sim 300\mu m$. In the case of Refel silicon carbide (Kennedy 1978) the critical flaw size is $\sim 20\mu m$. This order of magnitude difference in flaw size gives a scaling factor for the homogeneity of the microstructures.

Perhaps a clearer demonstration of this is as follows. If the criteria of failure is observed to be 1 millistrain and the empirical evidence of acoustic emission is taken to indicate that the size of structural features when the type of behaviour changes is 100μm and a fracture surface energy of 10-20 Jm^{-2} is appropriate,then it follows from equation (2) that the modulus of the material will be 25-50 GNm^{-2}. Now, clearly, fracture conditions cannot affect modulus, but structural features can. The combination of features present, such as phases and porosity, thermal and elastic anisotropy, etc., not only determine the bulk modulus but also the form of the fracture response. Thus, for materials like self-bonded silicon carbide, dense aluminas etc., the high modulus reflects the overall coherence of the structure. For ceramics of elastic modulus below 50 GNm^{-2} the homogeneity of the structure is not maintained and the mechanical response of the whole to external loads breaks down from a uniform elastic field to complex fields transmitted by various structural components. This also gives rise to fracture events (and, hence, acoustic activity) that are not catastrophic with respect to the sample as a whole. It has been observed in some of these structures (Alderson 1977) that there is an apparent connection between the nominally independent mechanical properties of strength, toughness and modulus. This is a further confirmation of the overall dependence of the properties on averages over the contributions of the microstructural components.

CONCLUSIONS

The assumptions made in producing design data for ceramic materials have not only to be reconsidered as Davidge (1980) has indicated, but also justification of the appropriate scaling factor for selecting fracture models has to be included. Where mechanical strength is of paramount importance, such as in engineering ceramics, the production of fine structured, dense materials ensures that the materials will all be of the homogeneous variety and so we are justified in developing and improving current models. However, the vast bulk of commercially very important ceramic and related materials, such as clayware, refractories, graphite, cement and building stone do not fall into the elastically homogeneous type. Nevertheless, for these materials, the prediction of load bearing capacity may well be of equal significance. Thus there is a strong case for examining the fundamental features of failure and sub-critical (non-catastrophic) fracture events, and their summation for design criteria, in detail.

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