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Universal fatigue curves for ceramics using indentation flaws

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In a recent series of papers [1–6] a methodology has been developed, using controlled indentation flaws, for evaluating crack velocity parameters from fatigue† strength data. The initial work [1, 2], on glass, established the fracture mechanics basis of the approach from which these evaluations could be made, with emphasis on the exceptional degree of accuracy attainable. An attempt was subsequently made to generalize the fracture mechanics formulation, taking into account the residual contact stresses about the flaws, by numerical integration of the fatigue differential equations [3]. The validity of the ensuing solutions was then tested on a glass ceramic in a case study [4]. Following this, a systematic investigation was made of the role of flaw size in the failure mechanics, once more using glass as a model test material [5]. It was thereby shown that data over an extensive range of indentation loads could be conveniently reduced onto a "universal fatigue curve" for each material. The scheme for the data reduction was analogous to that originally proposed by Mould and Southwick [7], except that now the plotting parameters could be related explicitly to intrinsic material properties. Finally, a more complete theoretical analysis of the underlying fatigue equations, following the realization that solutions could be derived in closed form, was presented as a basis for placing the procedure on a more rigorous footing [6].

In the present paper we indicate how the universal fatigue curves may be used to make comparative evaluations of different ceramic materials. Evaluations of this kind are often difficult to make, owing to the variability in natural flaw distributions. We illustrate the approach by considering results for two ceramics of technological importance, alumina‡ and silicon carbide§, in relation to the glass ceramic¶ data reported earlier [4].

Accordingly, controlled-flaw fatigue tests were run as follows [4]. Specimens were prepared as bars with polished surfaces for four-point flexure. Each bar was indented at the centre of its prospective tensile face with a Vickers pyramid so as to generate a "well-developed" radial crack pattern. The indentation loads chosen were 20 N for the glass ceramic, 10 N for the silicon carbide, and 20, 10 and 5 N for the alumina; this use of more than one load in the last case was simply to provide a self-consistent check of the universal plotting scheme. The fatigue tests were run in water at specified stressing rates; inert strengths for baseline reference were similarly run in dry nitrogen or silicone oil. Simple beam theory was used to calculate the maximum tensile stress in each specimen from the breaking load**.

The measured strengths, σ_f, are plotted as a function of stressing rates, $\dot{\sigma}_a$, in Fig. 1, with indentation load, P, incorporated into the coordinates in accordance with the universal fatigue relation for controlled flaws [5],

$$\sigma_f P^{1/3} = (\lambda'_P \dot{\sigma}_a)^{1/(n'+1)} \qquad (1)$$

Here n' and λ'_P are load-independent parameters for a given material/environment system, obtainable from the slope and intercept on the logarithmic plot. Each data point in this figure represents the mean and standard deviation of 5 to 15 tests at each specified value of $\dot{\sigma}_a P$. The solid lines are least-squares fits to the data for each material, and the shaded bands are appropriate inert strength levels.

Fig. 1 has immediate value as a graphic indicator

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†The term "fatigue" here refers to the time dependence of strength as a function of applied stress or stressing rate.

‡AD 96, Coors Porcelain Co., nominal grain size 10 μm.

§NC 203, Norton Co., grain size 4 μm.

¶Pyroceram C9606, Corning Glass Co., grain size 1 μm.

**For the alumina bars, which were received in thin substrate form, it was necessary to include a specimen thickness correction term in the strength evaluation. This correction never exceeded 6%.

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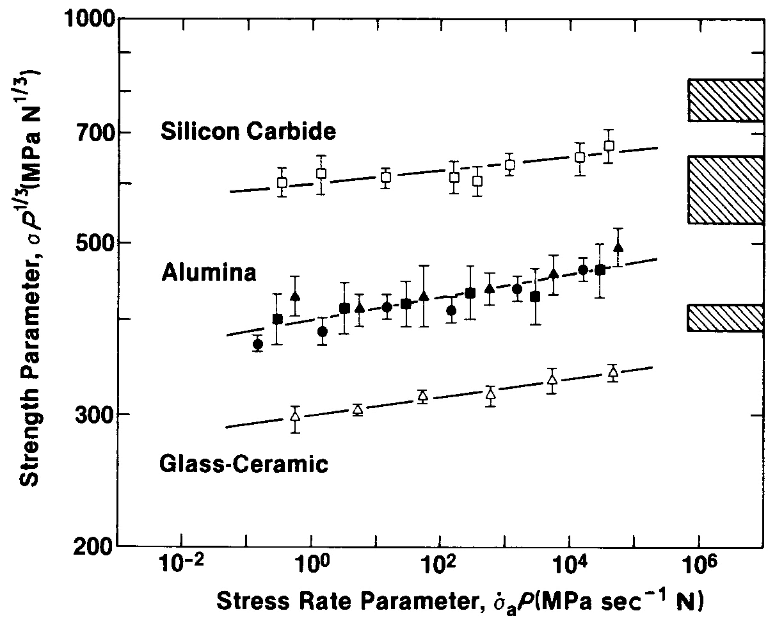

Figure 1 Universal fatigue curves for three ceramics, tested in water. Vickers indentation loads $P = 5$ N (circles), 10 N (squares) and 20 N (triangles).

of relative material properties. Thus, for any given combination of flaw severity (characterized here by P) and time dependence in the applied stressing (characterized by $\dot{\sigma}_a$), it is clear that silicon carbide, followed by alumina, has the superior strength properties. From a more quantitative standpoint, it can be shown [6] that the slope and intercept parameters in Equation 1 relate explicitly, via a set of "transformation equations", to the exponent and coefficient in a power-law crack velocity function. Likewise, the height of the inert strength plateau relates to the material toughness [8]. Accordingly, the universal plotting scheme contains all the information for complete characterization of both the kinetic and the equilibrium fracture responses for ceramic systems. A more extensive treatment of this kind of characterization will be presented elsewhere [9].

Another feature which is evident in Fig. 1 is the relative degree of scatter in the data for the three materials. This scatter trend appears to correlate with grain size (see earlier footnote). For alumina, the material with the greatest variability, microstructural influences were readily apparent as disruptions to the ideal radial crack geometry [10]. Such complications, while clearly not conducive to optimal accuracy in fracture parameter evaluations, may nevertheless take us one step closer to the configurations of naturally occurring flaws, thereby giving us added confidence in applying results from controlled indentation tests to real materials.

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