Comments on "Sub-critical crack extension and crack resistance in polycrystalline alumina"

Hübner and Jillek [1] have recently reported a dependence of critical stress intensity factor, K_{IC}, on subcritical crack extension in a polycrystalline alumina (Degussit AL23; average grain size = $18\,\mu$m). The dependence was found only for natural crack depths of about 0.5 mm or greater. Experimentally, Hübner and Jillek induced cracks of varying depths, Δc, in notched bend specimens by stable crack propagation from the notch root, and then determined K_{IC} from each specimen's compliance when the crack became unstable in bending with a high cross-head speed. They found K_{IC} to be $3.8\,\mathrm{MN\,m^{-3/2}}$ for $\Delta c = 0$ (no induced crack) and $\sim 6.0\,\mathrm{MN\,m^{-3/2}}$ for $\Delta c = 1.0$ mm*.

The purpose of the present note is to provide further information about this phenomenon, as obtained in fracture studies on two other alumina ceramics. One ceramic, a finer-grained (1 to $2\,\mu$m) hot-pressed material of similar purity (>99% alumina)† exhibited the phenomenon, but the increase in K_{IC} occurred at much smaller crack depths. The other ceramic, 3M Company's Alsimag 614‡, was less pure (~96% alumina), conventionally sintered material that was also finer grained ($5\,\mu$m average) than the Degussit material. It gave no evidence of an effect of subcritical crack growth on K_{IC} over a wide range of crack depths.

Rectangular specimens of the two ceramics were strength-tested in 3-point bending. The tests were conducted in dry N_2 at a stress rate of $100\,\mathrm{MN\,m^{-2}\,sec^{-1}}$ to restrict moisture-assisted subcritical crack growth, and in distilled water at $4\,\mathrm{MN\,m^{-2}\,sec^{-1}}$ to enhance such growth. Load was applied normal to the hot-pressing direction in testing the hot-pressed specimens. After strength testing, fracture mirrors were measured using optical microscopy, and K_{IC} values were determined for individual specimens from the following relations [2]:

$$K_{IC} \simeq \frac{A}{2.35} \tag{1}$$

TABLE I

Environment	σ_f ($\mathrm{MN\,m^{-2}}$)*	K_{IC} ($\mathrm{MN\,m^{-3/2}}$)
Dry N_2	825 ± 50	4.15 ± 0.20
Water	615 ± 45	4.98 ± 0.38

*Only specimens which failed from surface origins at mid-span are considered.

and

$$A \simeq \sigma_f r^{1/2} \tag{2}$$

where σ_f is fracture stress and r is mirror radius.

For eight specimens of the hot-pressed material tested in each environment, average values of K_{IC} and σ_f were as shown in Table I. Using the above values of K_{IC} and σ_f, the Griffith–Irwin equation [3] gives average critical crack depths for penny-shaped surface cracks of 16 and $41\,\mu$m (0.041 mm), respectively, for specimens tested in dry N_2 and water.

Both the higher average K_{IC} value and the larger dispersion among K_{IC} values from water tests are consistent with the finding of Hübner and Jillek that K_{IC} increased with the amount of crack extension due to subcritical crack growth. Further, the critical crack depths in this ceramic an order of magnitude smaller than those in the Degussit ceramic at which the phenomenon was found to occur is consistent with Hübner and Jillek's explanation attributing the phenomenon to crack branching along grain boundaries. The extent of such branching should depend on grain size, suggesting that the onset of increasing K_{IC} would be controlled by the ratio of critical crack depth to grain size, c/G. In this ceramic, K_{IC} was 20% higher at $c/G \simeq 25$ than at $c/G \simeq 10$. Hübner and Jillek found the most pronounced increase in K_{IC} of the Degussit ceramic at ratios from 20 to 50.

Extensive evaluations of K_{IC} from strength tests of the less pure Alsimag 614 ceramic have been reported elsewhere [4, 5]. Critical surface crack depths in the specimens ranged from about 50 to $150\,\mu$m, giving c/G ratios from 10 to 30, depending principally on whether testing was conducted in dry N_2 or water. Calculations of K_{IC}

*Since the term K_{IC} implies instability of single sharp crack, its use is perhaps inappropriate in the case of cracks where Hübner and Jillek observed three-dimensional crack branching.

†Supplied by Avco, Boston, Mass., USA.

‡Supplied by Technical Ceramics Division, Chattanooga, Tenn., USA. Alsimag 614 is believed to have a glassy phase at grain boundaries.

from σ_f and r or c values obtained on individual specimens indicated it to be a material constant, $\simeq 3.85\,\text{MN}\,\text{m}^{-3/2}$, suitable for predicting σ_f or c for water-tested specimens from values obtained in dry N_2 tests. This indicated absence of a dependence of K_{IC} on critical crack depth in the Alsimag 614 suggests that occurrence of the phenomenon in the alumina ceramics is associated with microstructural other than grain-size effects. Previously, the same effect was noted in pre-notched rock specimens and attributed to a smooth increase in the amount of subsidiary microcracking as the main crack advanced [6].

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Crazing under applied compression

Observations of crazing in a glassy polymer in a non-dilational stress field [1, 2] appear to be at variance with stress field criteria for crazing [3, 4] which require a positive value of the first stress invariant I_1. A critical value of the hydrostatic stress component, $\sigma_m = I_1/3$, also satisfies the conditions for the cavitation process [5] which is involved in craze formation. It may be possible to reconcile these observations with theory since crazes initiate from stress-raising flaws and the local stress field may be dilatational even if the applied stress system is not.

In order to examine this possibility, tests have been carried out with a non-dilational applied stress, i.e. uniaxial compression, using a specimen geometry which produces stress reversal at predetermined positions. Specimens of poly(methacrylate) (PMMA) of dimensions 10 mm by 10 mm by 3.2 mm thick with a 2 mm diameter central hole were normalized at 150° C and tested at 20° C. Tests were carried out at a strain rate of $10^{-2}\,\text{sec}^{-1}$ in a testing machine fitted with a compression cage and the specimens were illuminated and were viewed under load with a microscope.

Crazes initiated at a net section stress of $128\,\text{MN}\,\text{m}^{-2}$ and it was observed that they formed at the extremities of the vertical diameter as indicated by A in Fig. 1. The maximum tensile stress in the specimen is normal to the craze direction and the local value of I_1 at initiation is positive. Analysis of the elastic stress field at the craze tip suggests that it is possible for the craze to propagate in an entirely compressive stress field. However, this analysis is not complete as it does not take into account the stress field perturbation due to the craze. It is not yet possible to quantify this

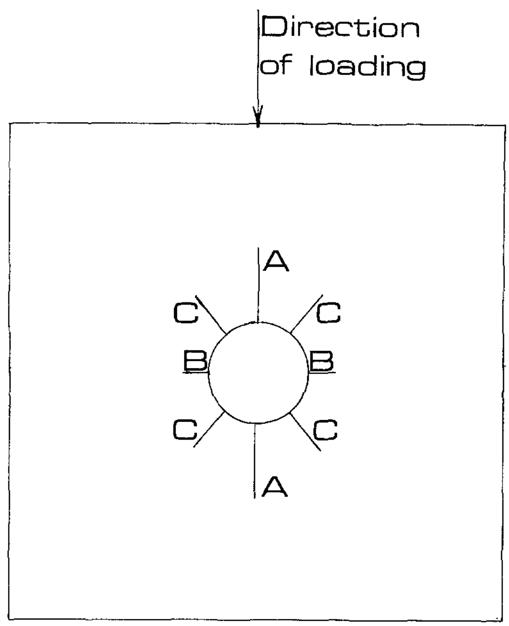

Figure 1 Schematic representation of microdeformation in the relaxed specimen.