between crazing and yielding [2–4]. Tables II and III of [2] show that the shear lip contribution is between 16 and 32% of the total.

I am indebted to Professor Hertzberg and his colleagues for their kind acknowledgment of my comments on the first draft of their comments [5] on our fatigue paper [2]. I am pleased to confirm that we did not intend to convey the impression that shear lip development was the sole cause of the improved fatigue crack growth resistance with increasing molecular weight. I had hoped that we had made it clear that both the shear lip contribution and the plane strain craze contribution are important, as stated in the abstract to [2]. Finally, we are entirely in agreement with Professor Hertzberg and his colleagues with regard to the importance of a load bearing network, and the presence of molecular entanglements.

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Comments on "Fracture stress-reflecting spot relations in hot-pressed alumina"

Kirchner and Richard [1] recently reported that the reflecting spot boundaries observed on Al_2O_3 fracture surfaces occured at $>K_{IC}$, as have Kirchner and Gruver [2, 3]. Thus they note that these boundaries cannot be the end of subcritical crack growth in contrast to their earlier suggestions that these boundaries may occur at K_{IC} [4]. However, Kirchner and Richard claim that variations in K along the reflecting spot boundary are inconsistent with these features being the "inner mirror", i.e. the analogue of the mirror–mist boundary on glass fractures. The purpose of this note is to point out that both the variation and size of the "reflecting spot" area are not inconsistent with this area being the "inner mirror". Furthermore, arguments are presented to show that the average size of the reflecting spot area may also be consistent with its being an inner mirror.

Rice [5] has recently summarized R_m/C data (where R_m is the "inner mirror" (mirror–mist boundary) and C is the flaw size) from several investigators on several polycrystalline materials (including Al_2O_3). R_m/C ratios were typically in the range of 4 to 8, and more commonly 5 to 7 in contrast to $\gtrsim 10$ for dense glasses. Materials having substantial to total transgranular fracture in the mirror region had increased intergranular fracture at and beyond the edge of the mirror region. It was proposed that this increase in intergranular failure was consistent with the concept of mist formation by secondary crack nucleation at, or ahead of, the main crack tip, as in glasses. However, it was pointed out that in polycrystalline materials, individual grains and grain boundaries would frequently be sources of crack nucleation. Thus, the local fracture energy for secondary crack nucleation would be the single crystal (γ_c) or grain boundary fracture energy (γ_B) in constrast to the polycrystalline fracture energy (γ_{pc}) typically required for the main (primary) crack. This difference in secondary versus primary crack γ values in polycrystals in contrast to a single, uniform γ value for both types of cracks in glass quantatively agreed with the R_m/C ratio differences between polycrystals and glasses.

The general observations of Kirchner and co-workers are consistent with Rice's model, and some provide direct support for it. First, although there are a variety of complications in analysing Al_2O_3 data (discussed below), the data of Kirchner and co-workers does show increase in intergranular failure at distances of 4 to 9 times the apparent flaw size (i.e. at stress intensities of approximately 2 to 3 times those at the boundary they identify as the original flaw in their analysis),

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which is generally consistent with Rice's evaluations. Second, features identical to fracture mirrors on Al_2O_3 single crystals are observed on the transgranular fracture of some Al_2O_3 grains near and beyond the distance expected for the mirror boundary, i.e. 4 to 8 times C, but not significantly inside of these distances [3]. Such mirrors, contained within a single grain, strongly support the concept of secondary crack nucleation within (favorably oriented) grains at and beyond the mirror boundary, as in Rice's observations of other materials. Third, contrary to their claims, the variation in K around the reflecting spot boundary is a consistent, intrinsic effect of the model proposed by Rice.

The concept of nucleation of secondary cracks on the scale of, or less than, the grain size as the mechanism of generating mist, and hence mirror boundaries, means that the stress intensity of such boundaries will vary around that boundary. As noted earlier, such secondary crack nucleation involves the local fracture energy pertinent to the scale of the grains. This will vary intrinsically due to the type of grain boundary (i.e. degree of twist and tilt), and its orientation, or the orientation of low energy single crystal (grain) fracture planes for inter- and transgranular cracks, respectively. Extrinsic factors such as grain-boundary second phase (pores, additives, impurities, etc.) will further verify this. Also, the grain size, which has a significant statistical variation, may effect such secondary crack nucleation, e.g. as observed for spontaneous cracking [6]. Thus, one would expect a diffuse mirror boundary with considerable local fluctuations about the mean stress intensity along the boundary as observed.

Several complications that limit numerical analysis of the data of Kirchner and co-workers should be noted. First, pores were the fracture origins in some of the samples that they analysed (e.g. R–4 and N–7). There are uncertainties in the size of peripheral cracks associated with such pores and in which resultant stress intensities to use [7, 8], contrary to some models. Second, some of their fracture origins (e.g. N–7) involved larger grains, which means that the pertinent critical stress intensity may be decreasing from the polycrystalline value toward typical single crystal or bi-crystal values [9]. Third, and most generally, the inherently anisotropic thermal expansion of the Al_2O_3 grains results in significant microstructural stresses that have been reported to decrease the critical stress intensity for failure to a value below that of the normal polycrystalline one, when flaw sizes decrease below a reasonable statistical sampling of grain orientations [10].

Consideration of these effects either increases, or does not reduce, the consistency of their results with the suggestion of this note; namely that K, R_m and C are consistent with $R_m/C < 10$ and with the average "reflecting spot" boundary (RSB) being R_m. First, consider stress intensity (K) values. If the RSB $\sim R_m$, the stress intensity at these boundaries should be $\geqslant 2\,K_{IC}$ to be consistent with $R_m/C > 4$ (but < 10). Their analysis gives approximately $1.5\,K_{IC}$. Possible higher K_{IC} values at the origin due to expansion stresses and deviations from pores and peripheral crack-penny flaw equivalence would raise the stress intensity values estimated at the reflecting spot (mirror) boundaries. Increases of $\geqslant 50\%$ seem likely (also reinforcing evaluations that these boundaries are not the termini of subcritical crack growth [1–3]. The least frequent effect of larger grains at the origin (which complicates evaluation of failure from some of the pores, e.g. N–7) cannot be evaluated from a stress intensity standpoint since the distance a crack must travel to reach γ_{pc} is unknown. However, as shown by R_m/C considerations below, such effects are consistent with the proposal of this note.

Second, consider C values and resultant R_m/C ratios. If the reflecting spot boundaries are mirror boundaries according to this proposal, R_m/C ratios should be < 10, e.g. up to approximately 60% less. Using the actual sizes of pores at origins as C gives R_m/C ratios of 5 to 10 (e.g. R–4, and N–7). Since the pore size is clearly a lower limit on the flaw size, but the true flaw size is likely to be less than twice the pore size, the R_m/C ratio is clearly < 10, and probably in good agreement with the observations of Rice. For failure involving large grains, the crack size where K is the polycrystalline value must be larger than the original flaw size, which would also reduce R_m/C values below 10. Thus, evaluation of their results shows that, despite significant uncertainties, they may either be consistent with, or directly support, the concept of the reflecting spot area being analogous with mirrors on glass fracture but with R_m/C less than glass values (i.e. < 10) due to lower local fracture energies for mist (secondary crack) generation.

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