Journal of the European Ceramic Society 7 (1991) 17–20

Fundamental Condition for the Existence of Microcrack Clouds in Monophase Ceramics

Brian R. Lawn

Ceramics Division, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA

(Received 23 April 1990; revised version received 3 July 1990; accepted 23 July 1990)

Abstract

Conditions for the existence of a microcrack cloud about a primary crack front in monophase polycrystalline ceramics are examined. With the assumption that microcracks initiate from sub-facet flaws, and that these flaws scale with the grain size, an expression is derived for the cloud radius. The cloud radius diminishes rapidly with grain size, from unlimited dimensions at the critical size for spontaneous, general microcracking to sub-grain level at some fraction of the critical size. The corresponding grain-size 'window' is dependent on the flaw size but is restrictively small for typical monophase ceramics.

An einphasigen polykristallinen keramischen Werkstoffen werden die Bedingungen zur Ausbildung einer Zone von Mikrorissen um die primäre Rißfront untersucht. Eine Gleichung zur Berechnung des Radius dieser Zone wird abgeleitet. Dabei wird von der Annahme ausgegangen, daß die Mikrorisse von Gefügefehlern herrühren und daß diese Fehler mit der Korngröße zunehmen. Der Radius dieser Zone nimmt mit der Korngröße rasch ab. Der Maximalwert eines 'unendlichen' Radius liegt bei einer kritischen Korngröße, bei der im gesamten Gefüge spontane Mikrorißbildung eintritt. Der Minimalwert beträgt nur einen Bruchteil der kritischen Größe und ist kleiner als die Korngröße. Der entsprechende Korngrößenbereich hängt von der Fehlergröße ab, ist aber für typische einphasige keramische Werkstoffe sehr eng.

On a examiné les conditions d'existence d'un nuage de microfissures au voisinage d'un front de fissure primaire dans les céramiques cristallines monophasées. En supposant que les microfissures sont initiées par des défauts subsurfaciques et que ces défauts sont proportionnels à la taille de grains on peut établir une expression du rayon de ce nuage. Ce rayon diminue rapidement avec la taille des grains, allant d'une dimension infinie pour une taille critique de microfissuration générale spontanée à une dimension subgranulaire pour une taille inférieure à la taille critique. La 'fenêtre' de taille de grains corespondante dépend de la taille du défaut mais est étroite pour les céramiques monophasées typiques.

Frontal-zone microcracking has been proposed as a mechanism of toughening[1–5] and consequent source of R-curve behaviour[5] in polycrystalline ceramics. In principle, individual microcracks can be activated at incipient sources, e.g. sub-facet grain-boundary flaws, in the field of a primary crack. The primary-crack stresses may be augmented by internal residual tensile stresses from differential thermal expansion or elastic mismatch. In relieving these tensile stresses, the fully developed microcracks remain irreversibly open, typically over several grain dimensions, thereby imposing a dilatant closure field on the primary crack.[5]

The issue of microcracking involves two fundamental questions: (i) *Under what conditions will a microcrack cloud exist*? (ii) *Given that such a cloud does exist, what is the extent of toughening*? The second of these questions has been frequently addressed, the first rarely. Thus the vast majority of studies *presume* the existence of a microcrack cloud. After all, above a critical grain size, many non-cubic ceramics do exhibit general, spontaneous microcracking throughout the material. However, definitive experimental supporting evidence for microcrack cloud zones in ceramics is almost totally lacking. Moreover, recent *in-situ* observations of propagating cracks in aluminas and other R-curve

Journal of the European Ceramic Society 0955-2219/91/$3.50

ceramics[6,7] (previously considered prime candidates for microcracking[5]) reveal no evidence whatsoever for active frontal zones; on the other hand, considerable grain-interlock bridging activity *is* observed at the crack interface behind the crack tips. Those observations have led some to question the very existence of microcrack clouds in ceramic materials.

In the present note, we consider this last point: what *are* the underlying conditions for the existence of a microcloud zone? For simplicity, we focus on monophase ceramics, although the principles to be outlined below extend to multiphase ceramics and, indeed, to other frontal-zone toughening processes (e.g. transformation toughening).

Consider a *monophase* ceramic material with predominantly intergranular fracture. For generality, suppose the material to be *non-cubic*, to allow for any thermal-expansion anisotropy stresses. We investigate the critical condition for microcrack initiation from the perspective of an observer at the tip of an equilibrium primary crack (P) looking outward towards potential sources (M) at (r, θ) (Fig. 1). The stress σ^M acting on a particular active source, assumed to be located at a grain-boundary sub-facet, is the superposition of two contributions:

(i) The mean (hydrostatic) tensile near-tip stress, $\bar{\sigma}_{ii} = (\sigma_{rr} + \sigma_{\theta\theta} + \sigma_{zz})/3$, in the polar field of the primary crack, evaluated from the Irwin displacement equation for a slit-like crack[8] at $K = K^P$,

$$\bar{\sigma}_{ii} = K^P \bar{f}_{ii}(\theta)/(2\pi r)^{1/2} \tag{1}$$

with $\bar{f}_{ii}(\theta) = (2/3)(1+\nu)\cos(\theta/2)$. This stress component has a maximum value $\bar{f}_{ii}(\theta) = 0{\cdot}72$ at $\theta = 60°$.[9]
(ii) The tensile component of the thermal-expansion anisotropy stress is given by:

$$\sigma_R = E\Delta\alpha\Delta T/(1+\nu) \tag{2}$$

with $\Delta\alpha$ the differential expansion coefficient between adjacent grains and ΔT the temperature range through which the material deforms elastically during the first cooling cycle. Of course, $\sigma_R = 0$ for cubic materials.

Approximating the sources as uniformly stressed penny-shaped flaws of radius c_0, the critical stress-intensity factor for microcrack extension is:[8]

$$\begin{aligned} K^M &= 2\sigma_C^M(c_0/\pi)^{1/2} \\ &= 2(\bar{\sigma}_{ii} + \sigma_R)(c_0/\pi)^{1/2} = T_0 \end{aligned} \tag{3}$$

with T_0 the intrinsic grain-boundary toughness.

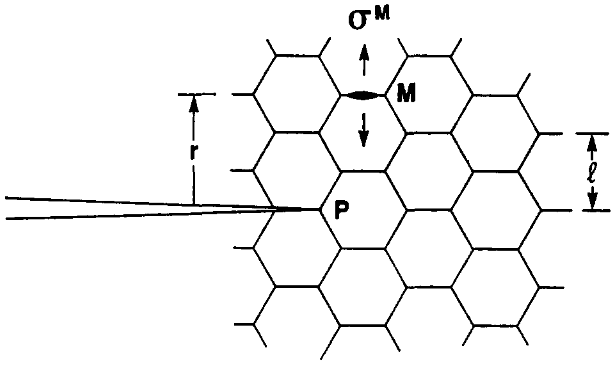

Fig. 1. Co-ordinates for evaluating microcrack initiation in polycrystalline material. Intrinsic penny-like microcrack flaw (M) at (r, θ), radius c_0 (not shown), subjected to superposed opening stresses σ^M from field of primary crack (P) and thermal-expansion mismatch stresses. It is assumed that the microstructure satisfies conditions of geometrical similarity at different grain sizes l, such that c_0 and r scale with l.

Mention was made of a critical grain size, l_C say, above which non-cubic ceramics tend to general microcracking during initial cooling. It is accordingly of interest to determine the conditions for microcracking in the absence as well as in the presence of a primary crack, to establish an upper bound to the scale of the frontal cloud. Suppose that the dimensions c_0 and r in Fig. 1 scale directly with grain size l, i.e. in accordance with the principles of geometrical similitude, so that the corresponding normalised quantities

$$\mathscr{C}_0 = c_0/l \tag{4a}$$

$$\mathscr{R} = r/l \tag{4b}$$

are scale-invariant. We may then distinguish between spontaneous and activated microcracking, as follows:

(i) *Spontaneous (general) microcracking.* In the absence of any primary crack ($\bar{\sigma}_{ii} = 0$), sources M initiate at tensile sub-facets from the sole action of the internal stress ($+\sigma_R$). Equation (3) is then satisfied at the critical grain size

$$l_C = (\pi/4\mathscr{C}_0)(T_0/\sigma_R)^2 \tag{5}$$

Above l_C, general microcracking occurs from active sources throughout the material. Taking typical values for alumina, $T_0 \approx 2{\cdot}0\,\mathrm{MPa\,m^{1/2}}$, $\sigma_R \approx 250\,\mathrm{MPa}$, $\mathscr{C}_0 \approx 0{\cdot}5$ (say), we obtain $l_C \approx 100\,\mu\mathrm{m}$ in eqn (5); this is of the order of the critical grain size observed experimentally. We note that, whereas some grain facets are in tension ($+\sigma_R$), others will be in compression ($-\sigma_R$), so that the initiated microcracks arrest at neighbouring facets (incipient bridging sites[10,11]) after extending approximately 3–5 grain diameters.

(ii) *Activated (cloud) microcracking.* Now consider the grain-size domain $l \leq l_C$. Active microcracking is confined to a cloud around the tip of primary crack P, within a maximum radius determined by inserting $K^P = T_0$ in eqn (1) and combining with eqn (3);

$$\mathscr{R}_C = 2\mathscr{C}_0\{\bar{f}_{ii}/(\pi[1-(l/l_C)^{1/2}])\}^2 \tag{6}$$

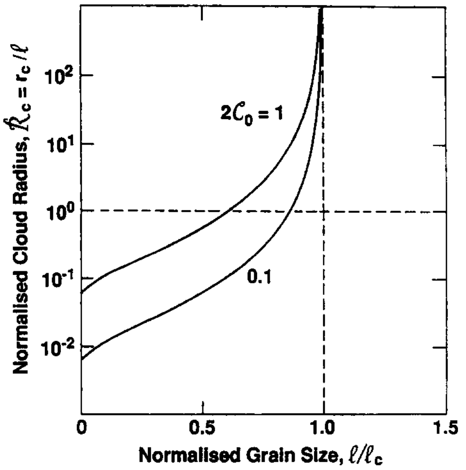

Fig. 2. Microcrack clould radius around primary crack tip as function of grain size, for two values of penny-flaw diameter.

We plot $\mathscr{R}_C$ as a function of l/l_C in Fig. 2, at two bounding values of $\mathscr{C}_0$, with $\bar{f}_{ii}$ evaluated at $\theta = 60°$ as above.

These calculations help to explain why microcrack clouds may not be as prevalent as generally presumed. In interpreting the plots in Fig. 2, we note that the condition $\mathscr{R}_C = r_C/l = \infty$ indicates an upper bound for general microfracture, as described by eqn (5); and $\mathscr{R}_C = 1$ indicates a lower level below which microcrack sources simply coalesce into the primary crack, i.e. there can be no detached cloud. With that, consider two limiting cases in eqn (6) as follows:

(a) $l/l_C \rightarrow 1$, $\mathscr{R}_C \rightarrow \infty$, corresponding to the limiting grain size for general microfracture

(b) $l/l_C \rightarrow 0$, $\mathscr{R}_C \approx 0{\cdot}1\mathscr{C}_0$, relating to materials for which $l \rightarrow 0$ or $l_C \rightarrow \infty$ ($\sigma_R \rightarrow 0$ in eqn (5)). Thus, since $\mathscr{C}_0 < 1$ generally, it follows that $\mathscr{R}_C < 0{\cdot}1$, so that *no* microcracking, spontaneous *or* activated, is expected in fine-grained or cubic materials. Physically, this is because the subfacet flaws lie too far distant (one grain dimension or more) from the primary-crack tip for the near field alone to be effective; decreasing the grain size brings the sources closer (eqn (4*b*)), but this is more than counteracted by a diminished flaw size (eqn (4*a*)).

Figure 2 shows that, between these limits, the cloud radius diminishes rapidly with decreasing grain size, more so at smaller c_0. Thus, for 'well-made' ceramics (small c_0) the 'window' of allowable grain sizes for the activation of significant clouds (at $r_C/l > 10$, say) may simply be too restrictive for common observation.

We are led to believe, especially in light of the current trend for materials processors to fabricate fine-grained, flaw-free microstructures, that microcrack-cloud toughening is unlikely to be a commonplace observation in monophase ceramics. Alternative toughening modes, e.g. grain-interlock bridging,[5,6] are not subject to the same restrictive windows and are therefore expected to dominate over the broader range of grain sizes.

In principle, the above analysis should be extendable to multiphase ceramics, and to other frontal-zone processes, with cosmetic adjustments to the treatment. It is conceivable that the flexibility afforded by the addition of a second phase (e.g. removal of necessity to conform to the restrictions of geometrical similarity) could facilitate an expansion of the grain-size window and thereby make microcracking a more viable prospect. In this context, it is interesting to note that the best-validated observations of microcrack zones in ceramics have been reported in two-phase systems.[12]

Acknowledgements

The author thanks S. J. Bennison, S. Lathabai and J. Rödel for comments and discussions. This work was funded by the U.S. Air Force Office of Scientific Research.

References

1. Hoagland, R. G., Embury, J. D. & Green, D. J., On the density of microcracks formed during the fracture of ceramics. *Scripta Met.*, **9** (1975) 907–9.
2. Evans, A. G., On the formation of a crack-tip microcrack zone. *Scripta Met.*, **10** (1976) 93–7.
3. Claussen, N., Steeb, J. & Pabst, R. B., Effect of induced microcracking on the fracture toughness of ceramics. *Amer. Ceram. Soc. Bull.*, **56** (1977) 559–62.
4. Evans, A. G. & Faber, K. T., Crack-growth resistance of microcracking brittle materials. *J. Amer. Ceram. Soc.*, **67** (1984) 255–60.
5. Clarke, D. R., A simple calculation of process-zone toughening by microcracking. *J. Amer. Ceram. Soc.*, **67** C15–16 (1984).
6. Swanson, P. L., Fairbanks, C. J., Lawn, B. R., Mai, Y.-W. & Hockey, B. J., Crack-interface grain bridging as a fracture resistance mechanism in ceramics: I. Experimental study on alumina. *J. Amer. Ceram. Soc.*, **70** (1987) 279–89.
7. Swanson, P. L., Crack-interface traction: A fracture-resistance mechanism in brittle polycrystals. In *Advances in Ceramics*, Vol. 22; *Fractography of Glasses and Ceramics*. American Ceramic Society, Columbus, Ohio, USA, 1988, pp. 135–55.
8. Lawn, B. R. & Wilshaw, T. R., *Fracture of Brittle Solids*. Cambridge University Press, Cambridge, UK, 1975, Chapter 3.

9. McMeeking, R. M. & Evans, A. G., Mechanics of transformation toughening in brittle materials. *J. Amer. Ceram. Soc.*, **65** (1982) 242–6.
10. Bennison, S. J. & Lawn, B. R., Role of interfacial grain-bridging sliding friction in the crack-resistance and strength properties of nontransforming ceramics. *Acta Metall.*, **37** (1989) 2659–71.
11. Chantikul, Prapaipan, Bennison, S. J. & Lawn, B. R., Role of grain size in the strength and R-curve properties of alumina. *J. Amer. Ceram. Soc.*, **13** (1990) 2419–27.
12. Ruhle, M., Claussen, N. & Heuer, A. H., Transformation toughening and microcracking as complementary processes in ZrO_2-toughened Al_2O_3. *J. Amer. Ceram. Soc.*, **69** (1986) 195–7.