CHANGE IN FRACTURE TOUGHNESS IN TWO PHASE CERAMICS BY MICROCRACK INTERACTION

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ABSTRACT

This paper investigates the change in fracture toughness in microcracked two phase ceramic composites. We followed the calculations of Pompe and Kreher, who obtained increase in fracture toughness in microcracked composites. We modified their calculations using the results a microcrack interaction model and predicted the decrease in fracture toughness with higher microcrack density. Our results are complementary to the results of Pompe and Kreher in predicting the optimum value of fracture toughness.

KEYWORDS

Fracture toughness; two phase ceramic composites; microcracking.

INTRODUCTION

The phenomenon of increased toughness in ceramics with controlled amount of microcracking is a very interesting one. This has been observed in various systems (Hoagland and others, 1973; Green and others, 1973; Evans and others, 1974). The word 'controlled amount' is very important in this context. The fracture toughness will increase whenever there is controlled amount of microcracking present. Otherwise, it will decrease.

In the literature, it is argued that the increase in toughness or fracture surface energy occurs because of dissipation of energy from the main crack to form microcracks. These were a few theoretical studies on toughening by microcracks. Initial numerical calculations were performed by Hoagland and others (1975) and Evans (1976). The important aspect of these two studies was the fact that the damaged zone that forms ahead of the crack tip behaves inelastically and is analogies to the crack tip plastic zone in metals. Energy is consumed by creating new surface area by mixed mode crack tip displacement against deviatoric and dialational components of the main crack. Buresch (1977a, 1977b) and Buresch and coworkers (1983) actually estimated increase in toughness by microcracking. The paper by Buresch and coworkers is a very important one where they developed the concept of J integral in the microcracked zone.

We will now recall the most important progress made in the understanding in microcracked ceramics. The first one is a computer simulation model developed by Hoagland and Embury (1980). This model removed the limitations of the previous models by considering the interaction between the microcracks and that between the macrocrack and the microcracks. The model predicts the number and the distribution of microcracks with stress and also predicts R-curve behaviour. They, however did not obtain values of change in toughness with microcracking.

The other important work is one by Pompe and Kreher (1981) which is an elaborate modification of the earlier work by Pompe and coworkers (1978). Pompe and Kreher performed detailed calculation of balance of energies at the process zone and predicted the change in fracture toughness with change in microcrack density. The interesting aspect of this theory is that it could almost reproduce the change in fracture toughness behaviour of Al_2O_3 - ZrO_2 composites of Claussen's (1976) experimental results. The work of Pompe and Kreher forms the basis of the present study and leads to the definition of the problem.

In this paper, we want to obtain the change in fracture toughness in two phase microcracked ceramics with change in microcrack-microcrack interaction. The comprehensive model of Pompe and Kreher did not consider this fact. The present paper tackles the problem of microcrack interaction by incorporating the computational results of Delameter and coworkers (1975). The model calculates the change in Young's modulus and in strain energy in an elastic solid having an array of cracks arranged in a rectangular fashion as shown in figure 1. Row and column spacings are also given in the figure . Variation in Young's modulus is given in figure 2. These values are then inserted in the Pompe Kreher theory.

THEORY AND CALCULATIONS

In this part, we will briefly discuss how we modified the theory of Pompe and Kreher and performed calculations. As mentioned earlier, the microcracked zone ahead of the crack tip does not show elastic behaviour. Since this zone is very small compared with main crack, small scale yielding approach could be applied. Then an energy balance around the process zone is done. The ratio of fracture surface energies are given by the following-

$$\frac{G_c}{2\gamma_0} = \frac{\gamma/\gamma_0}{1-\alpha\left[\dfrac{\eta_D+\eta_S-\eta_{SO}}{\sigma_c^2/(2E_0)}\right]} \quad \text{———— (1)}$$

where G_c is twice the fracture surface energy of the microcracked solid, γ_0 is the fracture surface energy of the original solid, γ is the fracture surface energy of the solid, α is a constant dependent on the dissipation process, η_D , η_S and η_{SO} are the densities for energy stored, dissipated inside the process zone and stored outside it respectively σ_c is the characteristic stress where dissipation starts and E_0 is the Young's modulus for the microcracked body. According to Pompe and Kreher

$$\eta_D+\eta_S-\eta_{SO} = \frac{\sigma_{mc}^2}{2E_0}\, g(N,V,\chi) \quad \text{———— (2)}$$

where σ_{mc} is the maximum tangential stress for microcracking g is a function of N, the microcrack density, V is the volume fraction of the second phase and χ, is the residual stress parameter.

For energy consideration,

$$g(N,V,\chi) = (1-V)\left[\frac{1-E/E_0}{E/E_0}\right] \times \left[1-\frac{5V\chi^2 E/E_0}{2\left[1+\left(\frac{1-V}{1+V}\right)\frac{E}{E_0}\right]}\right] \quad \text{———— (3)}$$

Pompe and Kreher used the results of Budianisky and O'Connell (1976), who calculated the Young's modulus for randomly oriented cracked elastic body. According to that model, $E/E_0 = 1 - 2/3\ N$ and the value is introduced into the equation. In this present work on the other hand, E/E_0 is calculated on the basis of the results of Delameter and coworkers. The final expression for increase in fracture surface energy is given by-

$$\frac{G_c}{2\gamma_0} = \frac{\gamma/\gamma_0}{1-\frac{1}{3}\left[\dfrac{g(N,V,\chi)}{\sigma_c^2/2E_0}\right]} \quad \text{———— (4)}$$

where g is given by the equation (3). The ratio of γ/γ_0 is given as $\gamma/\gamma_0 = 1 - 0.5\ N$ ———— (5)

The ratio of σ_c/σ_{mc} is given by

$$\sigma_c/\sigma_{mc} = 1-\frac{5}{12}(1+2v)\chi \quad \text{———— (6)}$$

where χ has been defined before. We can obtain a value of the change in fracture toughness by taking the square root of the right hand side equation (4). In this paper, we propose to study the aforesaid problem by dividing the situation into four subgroups-

(a) Effect of column spacing for constant row spacing-
  (i) Low 2a/b ratio
  (ii) High 2a/b ratio

(b) Effect of row spacing for constant column spacing-
  (i) Low 2a/d ratio
  (ii) High 2a/d ratio

Finally we will apply the results of the above model to see whether we can predict Claussen's results.

In present calculations, d values are chosen so as to get proper values for crack density. From the theory itself, the maximum value of N cannot be greater than 2. For a given d value, the change in Young's modulus is obtained from figure 2. Finally equation (3) is calculated. The ratio of σ_c/σ_{mc} is calculated from equation (6) assuming v=0.1 and χ =1.2

in accordance with Pompe-Kreher choice. Another reason for choosing χ =1.2 is that it is needed to analyze Claussen's data. The present scheme of calculations gives a decrease in the E/E_0 ratio with increase in microcrack density. This effect increases g and γ/γ_0. However increase in γ/γ_0 is more than that in the denominator. Thus the ratio $G_c/2\gamma_0$ is more than 1 in every case. The important difference between this model and the Pompe-Kreher model is that the latter describes the increase in toughening with increase in microcrack density which former predicts the decrease. This difference is there because our model considers the interaction of microcracks, where Pompe-Kreher model does not. Physically speaking, this decrease in fracture toughness with increase in microcrack density is quite obvious. When the microcrack density becomes more, they just collapse, increasing the compliance of process zone ahead of the crack tip. Experimental data, indeed, show that with change in microcrack density fracture toughness goes through a maximum and then decreases. To describe this entire behaviour both the models have to be applied.

DISCUSSION

In view of the above discussion, we can look into the results given in the figures 3(a), (b) and 4(a), (b). Figures 3(a) and (b) show the effect of column spacing for row spacing. The ratio of 2a/b is low (0.5) in 3(a) and high (2.0) in 3(b). In the former case, rows of cracks are further apart and hence the interaction should be smaller. This argument based on physical reasons, seems to be right in the cases of figures 3(a) and 3(b). In figure 3(a), the decrease in toughness is smaller as compared to 3(b). In figure 3(a), the d values are different. The amount of change in fracture toughness is however the same because it occurs during much larger change in density of microcracks. The result can also be explained in terms of microcrack interaction, as put forth above.

Figures 4(a) and (b) show the change in fracture toughness for crack configuration having the constant column spacing and variable row spacing. Again similar arguments can be invoked to explain the observed results.

From the above figures, we can see two prominent features - (1) when the microcrack density is quite high, the toughness decreases and (2) when rows and columns are close spaced i.e., the microcrack interaction is more, the decrease in toughness is also more.

The results enable us to duplicate the experimental data of Claussen from purely physical standpoint. K_c/K_{co} in the case of Claussen's data is about 1.2 to 1.4. Within the framework of the present paper 2a/b=2.0 and d=3.0 seem to be the most perfect. The results are plotted in figure 5. Volume percentage of ZrO_2 were calculated from N=f(v/1-v) where v is the volume percentage and f is a constant. Results are shown by a continuous line. When our model is applied to the case 2a/b=0.5, it fails. So we have plotted Pompe and Kreher's results superposed to our results. They cut at a point about 1.4 and 4 volume percentage. This point represents the maximum toughness achieved in the present case and agrees well with Claussen's data.

CONCLUSIONS

In this paper we attempted to predict the change in toughness in a two phase ceramics, having microcracks that interact. In short, this means applying Delameter and others' results to Pompe and Kreher model. The results show that (1) toughness increases with increase in microcracking (2) with increase in microcrack interaction, the decrease in toughness is more. The results were applied to explain Claussen's experimental data. To duplicate the data, two models-the one that considers no microcrack interaction and the one that takes into account microcrack interaction, should be superposed.

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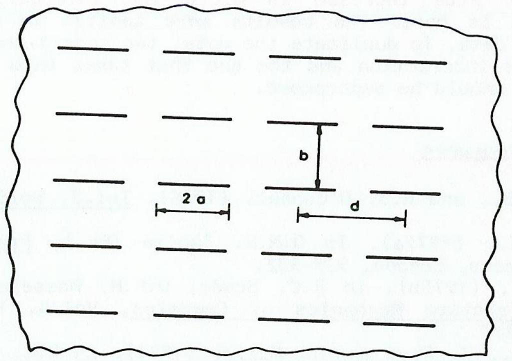

Figure 1

Rectangular array of cracks showing individual crack length (2a), distance between rows (b), and columns (d).

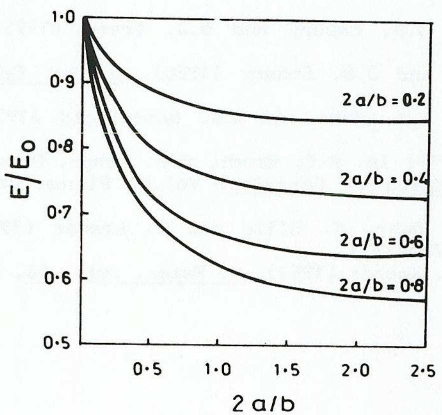

Figure 2

Variation of Young's modulus with row and column spacing.

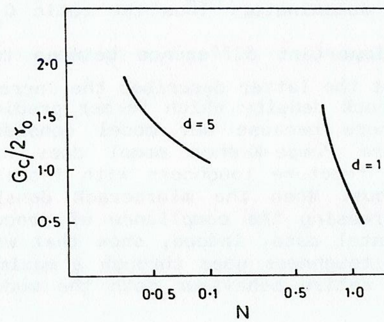

Figure 3a

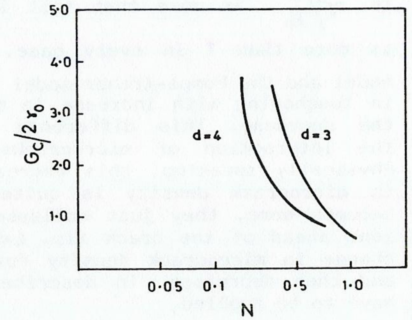

Figure 3b

Change in fracture surface energy with variable column spacing and constant row spacing (low 2a/b ration in 3a and high 2a/b ratio in 3b)

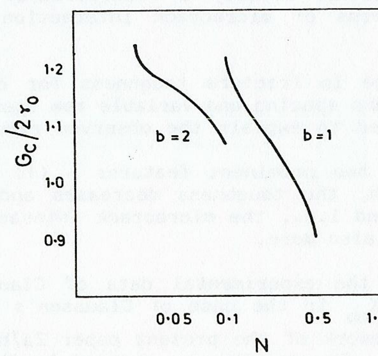

Figure 4a

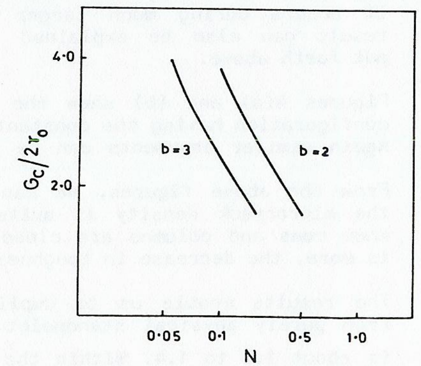

Figure 4b

Change in fracture surface energy with variable row spacing and constant column spacing (low 2a/d ratio in 4a and high 2a/d ratio in 4b)

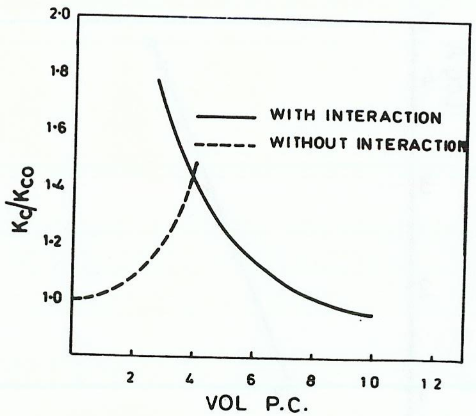

Figure 5
Variation of fracture toughness with volume percentage of ZrO_2.
Figure shows microcrack intearaction effects.