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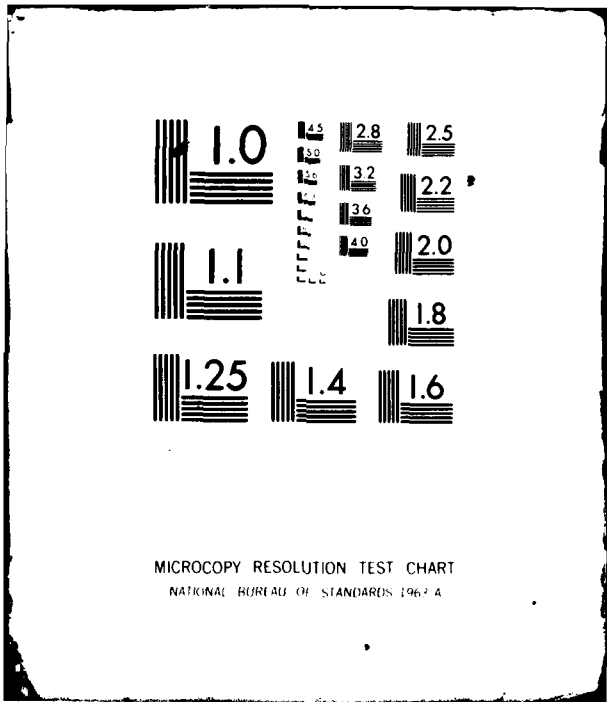
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TRANSFORMATION TOUGHENING  
PART 2: CONTRIBUTION TO FRACTURE TOUGHNESS

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ABSTRACT

Two approaches are taken to determine the contribution of a stress-induced phase transformation to the fracture toughness of a brittle material. Both approaches result in the expression:

$$K_c = \left[ K_0^2 + \frac{2RE_c V_1 (|\Delta G^c| - \Delta U_{se} f)}{(1 - \nu_c^2)} \right]^{1/2}$$

where  $K_0$  is the critical stress intensity for the material without the transformation phenomenon,  $(|\Delta G^c| - U_{se} f)$  is the work done per unit volume by the stress field to induce the transformation,  $E_c$  and  $\nu_c$  are the elastic properties,  $V_1$  is the volume fraction of retained, high temperature phase and  $R$  is the size of the transformation zone associated with the crack. It is assumed that only those inclusions (or grains) close to the crack's free surface will contribute to the fracture toughness; thus  $R \approx$  the inclusion size. The chemical free energy change associated with the transformation  $(|\Delta G^c|)$  will govern the temperature and alloying dependence of the fracture toughness.

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Figure 1 illustrates a section of the cracked body under tensile load which contains a uniform dispersion of untransformed inclusions of volume fraction  $V_i$ . It is assumed that the stress field associated with the crack front has caused inclusions to transform. As the crack extends and the stresses within the previously transformed zone decrease, inclusions that have lost some constraint by being either traversed by the crack or in close proximity to the new fracture surfaces will remain in their transformed state. This process leads to a transformation zone which surrounds the crack, as shown in Fig. 1. Only those inclusions which remain transformed will contribute to the non-recoverable work done by the loading system to stress-induce the transformation. Since the inclusion must lose constraint to remain in their transformed state once the crack's stress field moves, the size of the transformed zone ( $R$ ) is approximately equal to the inclusion size, viz.  $R \approx D$ .

Following Sack's solution to this same problem without the transformation phenomena, the increase in free energy of the body due to new crack surfaces is

$$U_s = \pi c^2 G_0 \quad , \quad (1)$$

where  $G_0$  is the critical strain energy release rate associated with the formation of new surface. The increase in strain energy due to crack extension is

$$U_{se} = \frac{8(1 - \nu_c^2) \sigma_a^2 c^3}{3E_c} \quad , \quad (2)$$



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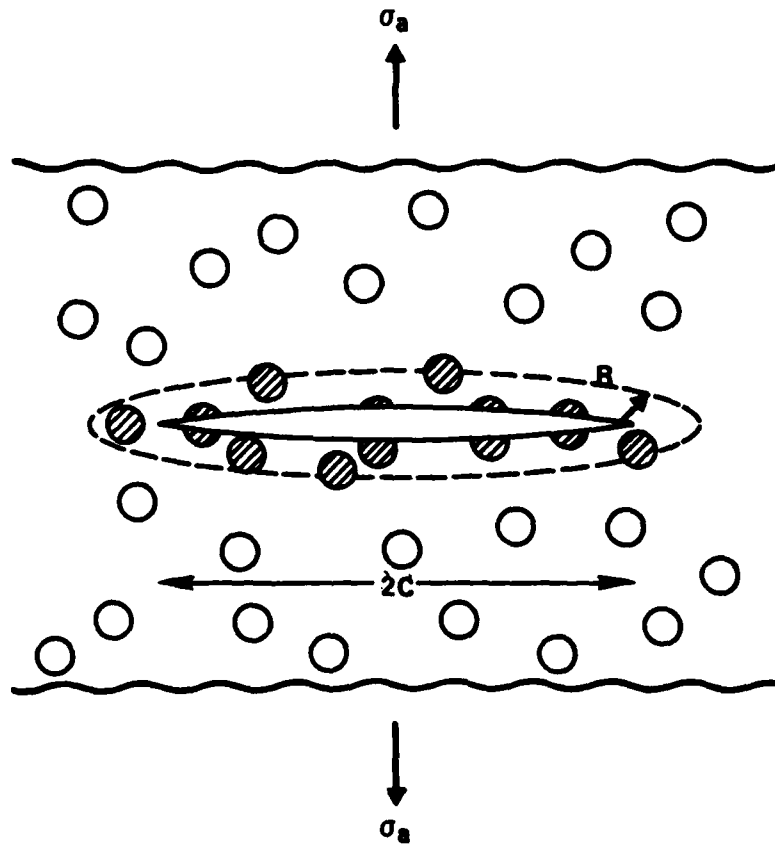


Fig. 1 Section of a penny-shaped crack of radius  $c$  within a stressed composite containing inclusions. Hatch inclusions have been transformed during crack extension.



where  $\sigma_a$  is the applied tensile stress and  $E_c$  and  $\nu_c$  are Young's modulus and Poisson's ratio of the composite material, respectively. The work done by the loading system, i.e., the decrease in the potential energy of the load, is

$$W_1 = - \frac{16(1 - \nu_c^2) \sigma_a^2 c^3}{3E_c} \quad (3)$$

An additional term arises when the transformation phenomena is included in the fracture process. Recognizing that the volume of the transformed zone is  $2\pi R(c+R)^2 = 2\pi Rc^2$ , this additional term is the work done by the loading system to form the transformed zone:

$$W_2 = -2\pi Rc^2 W \quad ,$$

where  $W$  is the work per unit volume of transformed material to induce the transformation. The minimum value of  $W$  is determined by

$$\Delta G_{t \rightarrow m}^C = -\Delta G^C + \Delta U_{se} f - W = 0 \quad (4)$$

where  $\Delta G^C$  is the chemical free energy change for the reaction  $ZrO_2$  (tetragonal)  $\rightarrow$   $ZrO_2$  (monoclinic),  $\Delta U_{se}$  is the change in strain energy associated with the transformation and  $(1 - f)$  is the loss of strain energy due to the loss of constraint imposed on the inclusions during crack extension. Thus,

$$W = -\Delta G^C + \Delta U_{se} f \quad (5)$$



and\*

$$W_2 = 2\pi R c^2 V_f (|\Delta G^C| - \Delta U_{sef}) \quad (6)$$

Summing Eqs. (1), (2), (3), and (6), we obtain the total energy of the system as a function of crack length:

$$U = \pi c^2 G_0 + 2\pi R c^2 V_f (|\Delta G^C| - \Delta U_{sef}) - \frac{8(1 - \nu_c^2) \sigma_a^2 c^3}{3E_c} \quad (7)$$

The condition for crack extension is determined by setting  $\partial U / \partial c = 0$ , which can be used to define the contribution of the stress-induced transformation to either the strength-crack size relation

$$\sigma_c = \left[ \frac{\pi E_c (G_0 + 2RV_f (|\Delta G^C| - \Delta U_{sef}))}{4(1 - \nu_c^2)c} \right]^{1/2} \quad (8)$$

or the critical stress intensity factor

$$K_c = \frac{2}{\sqrt{\pi}} \sigma_c \sqrt{c} = \left[ K_0^2 + \frac{2RV_f E_c (|\Delta G^C| - \Delta U_{sef})}{(1 - \nu_c^2)} \right]^{1/2} \quad (9)$$

where  $K_0 = [(G_0 E_c) / (1 - \nu_c^2)]^{1/2}$  is the critical stress intensity factor of the material without the transformation phenomenon.

\*The absolute brackets are used to indicate that the sign of  $\Delta G^C$  has already been defined as negative in Eq. (4) for the temperature range of interest.



3. Irwin's Approach

The same subject can be viewed with Irwin's approach,<sup>(4)</sup> where one imposes a force field to a stressed crack tip and calculates the work required to close it by a unit length. Irwin showed that the work per unit length of crack closure is equivalent to the net work dissipated per unit length of crack extension  $\partial(U_{se} - W_1)/\partial c$  as calculated through the Griffith approach. Fracture will take place when  $\partial(U_{se} - W_1)/\partial c > G_c$ , termed the critical strain energy release rate. The major difference between the two approaches is that in calculating the net work dissipated, Irwin only needs to consider the stress field in the vicinity of the crack tip, whereas the Griffith approach requires complete knowledge of the stress state in the system.

To apply the Irwin approach, let us consider the unit of crack to be closed to have traversed a transformed inclusion as shown in Fig. 2(a). The work to close this unit of crack can be broken into two parts, one concerned with the transformation ( $\Delta W_t$ ) and one concerned with crack closure ( $\Delta W_c$ ). The first force field we apply would revert the fractured inclusion back to its untransformed state as shown in Fig. 2(b). The work performed by this first force field per unit volume of transformed material is

$$W = |\Delta G^C| - \Delta U_{se} f \quad (10)$$

where  $|\Delta G^C|$  is the change in chemical free energy for reverting the  $ZrO_2$  inclusion from its monoclinic structure to its tetragonal structure.  $\Delta U_{se}$  is the strain energy associated with the transformation, and  $(1 - f)$  is that portion of



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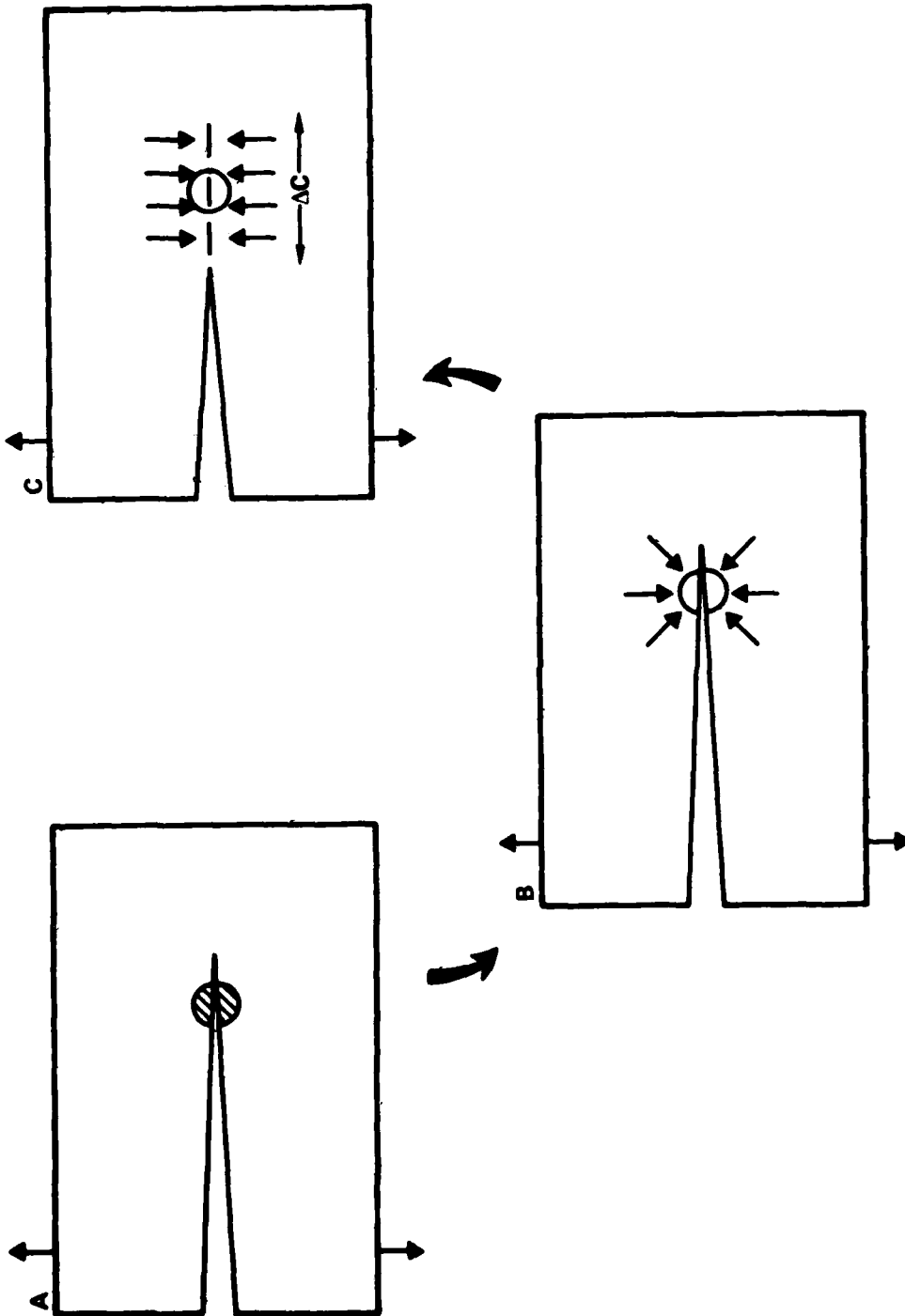


Fig. 2 Crack under fixed grip conditions which has (a) intersected a transformed inclusion (hatched). First force (b) field reverts the inclusion to its untransformed state. Second force field (c) closes crack by a unit length ( $\Delta C$ ).



the strain energy relieved during fracture. The total work done on all inclusions within the volume  $2R\Delta c$  per unit crack length is

$$\Delta W_t = 2R\Delta c V_i W = 2RV_i (|\Delta G^C| - \Delta U_{sef}) \Delta c \quad (11)$$

Once the inclusions have been reverted to their untransformed state, the strain energy associated with the inclusions disappear and the crack now looks like any ordinary crack in a two phase material. At this point, the second force field can be applied, as defined by Irwin, to close the crack by the unit length  $\Delta c$  as shown in Fig. 2(c). The work performed in this operation is

$$\Delta W_c = G_0 \Delta c \quad , \quad (12)$$

where  $G_0$  is the critical strain energy release rate for the composite material without the transformation phenomenon.

The total work for crack closure per unit crack length which also reverts the inclusions to their initially untransformed state is

$$\frac{\Delta W}{\Delta c} = \frac{\Delta W_c}{\Delta c} + \frac{\Delta W_t}{\Delta c} = G_0 + 2RV_i (|\Delta G^C| - \Delta U_{sef}) \quad . \quad (13)$$

Thus, the contribution of the stress-induced transformation to the critical strain energy release rate of the composite can be expressed as



$$G_c = G_0 + 2RV_i(|\Delta G^c| - \Delta U_{se}f) \quad (14)$$

or expressed as the critical stress intensity factor

$$K_c = \left[ \frac{E_c G_c}{(1 - \nu_c^2)} \right]^{1/2} = \left[ K_0^2 + \frac{2RV_i E_c (|\Delta G^c| - \Delta U_{se}f)}{(1 - \nu_c^2)} \right]^{1/2} \quad (15)$$

#### 4. Discussion

As expected, both approaches have led to the same expression for the critical stress intensity factor of a material containing inclusions that can undergo a stress-induced transformation. The expressions show that the contribution of the stress induced transformation can be maximized by maximizing a) the volume fraction ( $V_i$ ) of inclusions fabricated in their untransformed state, b) the elastic modulus ( $E_c$ ) of the composite, c) the factor ( $|\Delta G^c| - \Delta U_{se}f$ ) and, d) the size of the transformation zone ( $R$ ) associated with the propagating crack front. Each of these factors will be discussed in the following paragraphs.

Maximizing the volume fraction would result in a single phase, polycrystalline material, e.g., tetragonal  $ZrO_2$ . Here, the inclusions could be defined as individual grains, surrounded by neighboring grains of different misorientations which define the matrix. Each neighboring grain constrains one another from undergoing a stress-free transformation by their anisotropic transformation strains. Thus, from a conceptual viewpoint, a single phase, polycrystalline material can be treated in the same manner as described above.



The elastic modulus of the composite can be increased by choosing a chemically compatible second phase with a higher elastic modulus. For the case of  $ZrO_2$ ,  $Al_2O_3$ , with a modulus approximately twice that of  $ZrO_2$ , would be a desirable choice. But adding a second phase to increase the modulus would at the same time decrease the volume fraction ( $V_i$ ) of the toughening agent. One would, therefore, be concerned with the product of  $V_i E_C$  (Eq. (15)) in optimizing  $K_C$ . If we assume that the composite modulus is governed by the rule of mixtures, viz.  $E_C = E_i V_i + E_m(1 - V_i)$ , then the product would have the following form:

$$V_i E_C = V_i E_i [M - V_i(M - 1)] \quad , \quad (16)$$

where  $M = E_m/E_i$ , the modular ratio of the matrix (m) and the inclusion (i). Differentiating Eq.(16) with respect to  $V_i$ ,

$$\frac{\partial(V_i E_C)}{\partial V_i} = E_i [M - 2V_i(M - 1)] \quad , \quad (17)$$

shows that the maximum in the product relation occurs at  $V_i = 1$  when  $M < 2$ , i.e., the greatest toughness, with other factors constant, should be obtained for a single phase material. If  $M > 2$ , the toughness could be optimized when  $V_i < 1$ . On the other hand, if the objective is to toughen a matrix phase (e.g., toughening  $Al_2O_3$  with  $ZrO_2$ ), Eq. (16) shows that more toughening is obtained for a given volume fraction the greater the modular ratio. That is, small volume fractions (e.g.,  $V_i < 0.3$ ) of the toughening agent will produce greater results the greater the modulus of the matrix material.



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The dependence of fracture toughness on temperatures and alloy content will be governed by the factor  $(|\Delta G^C| - \Delta U_{se}f)$ . This is because, relative to other factors, the chemical free energy change  $(\Delta G^C)$  exhibits the greatest change with temperature and alloying content. For the  $ZrO_2(t) \rightarrow ZrO_2(m)$  reaction,  $|\Delta G^C|$  decreases with increasing temperature and alloying (e.g.,  $Y_2O_3$ ,  $CeO_2$ , etc) content. Thus, for this transformation, the fracture toughness is expected to decrease with increasing temperature as the factor  $(|\Delta G^C| - \Delta U_{se}f)$  decreases to zero. Likewise,  $K_c$  will decrease as the alloy content in  $ZrO_2(t)$  is increased. That is, fracture toughness will be optimized at the lower temperatures and for the least alloy content. The temperature where the contribution of the stress-induced toughness disappears will depend on the magnitude of  $\Delta U_{se}f$ . Phenomena that help relieve strain energy during the fracture, e.g., twinning, will decrease the value of  $f$  and thus increase the temperature where the contribution to toughness disappears.

The major assumption used in the model to derive the  $K_c$  expressions was that the size of the transformation zone ( $R$ ) was determined by the close proximity of the inclusions to the free surface formed during fracture. That is, inclusions transformed by the stress field would only remain in their transformed state. Once the crack's stress field passes, if much of their constraint was lost during crack extension. This assumption leads to the hypothesis that the zone size would be directly related to the inclusion size ( $D$ ), viz.  $R = D$ . It is, therefore, hypothesized that  $K_c$  will increase with increasing inclusion size.



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It can also be argued that if inclusions remote to the crack's surface were to remain in their transformed state, their residual strain energy would be greater relative to those adjacent to the crack surface. Thus, the work loss to the fracture process for remote inclusions would be less than for inclusions adjacent to the crack surfaces. That is, adjacent inclusions would contribute more to the fracture toughness than remote inclusions.

#### ACKNOWLEDGEMENTS

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