13th International Symposium on Ballistics
Stockholm, 1-3 June, 1992

135

DYNAMIC FRAGMENTATION OF ALUMINA: A SIMPLIFIED MODEL

Dr. Luis H.L.Louro (1), M.Sc. José R.A.Ribeiro (1), Dr. Marc A.Meyers(2)

(1) Instituto Militar de Engenharia, Pça. Gen. Tiburcic ...

Brazil, 22793, (2) University of California, San Die...

Mechanics and Engineering Science, R-011, La Jolla, C...

P. I.

In a series of impact experiments in which the stress level, stress duration, and alumina grain size were varied, the effect of these parameters on fragmentation of alumina were quantitatively established. The impact experiments were carried out by using both a gas-gun and an explosively-driven flyer plate. Crack initiation sites for damage were identified by transmission electron microscopy. A simplified model for fragmentation was developed, based on nucleation, growth, and coalescence of cracks. This model leads to quantitative predictions of damage trough the parameter S_v (macrocracks surface area per unit volume) that is a function of stress-wave and material parameters.

1.INTRODUCTION

Dynamic fracture in ceramics have received little attention and no comprehensive model of deformation and fracture in highly brittle materials at high strain rates has yet been developed. In contrast, spall fracture in metals has been extensively studied. The relative difficulty in recovering brittle targets for post-impact characterization has been pointed out (1) as the main reason why the understanding of dynamic fracture has lagged behind that of metals. The objective of this article was to develop a model for the ceramics fragmentation. This model is based on physical observations and correlations. The recent studies by Yaziv (1) and Louro (2) provide comprehensive reviews on the subject. The concept of nucleation, growth, and coalescence of cracks was apllied together with the concept of stress intensity factor built up at the crack tip. The consideration of an unloaded volume surrounding each growing crack led to a general formulation incorporating the stress pulse shape (both compressive and tensile) on fragmentation. This simplified model lead to quantitative predictions of fragmentations.

2. EXPERIMENTAL PROCEDURE

The experiments were conducted both in a one-stage gas-gun at velocities between 200 an 1,000 m/s and by using an explosively-driven flyer plate generating pressures ranging from 4.3 GPa to 11 GPa. The experimental set-ups were designed in order to promote planar impacts. The specimens (disk-shaped) were encapsulated into aluminum containers as illustrated in Figure 1 for gas-gun experiments. Projectiles were of the same materials as capsules, as well as the momentum traps. Matching of surfaces between alumina and capsule was very carefully conducted, with individual matching of pairs, in order to decrease, to the extent possible, existent gaps. After impact, the capsules were sectioned and the capsule-alumina sets were impregnated with a dark resin in a vacuum oven in order to more clearly delineate cracks. Crack observation was conducted at three levels: macro, meso, and microscopic. Only macroscopic measurements, based on the linear intercept method, are reported here.

3. EXPERIMENTAL RESULTS

The most significant results are shown in Figures 2, 3, 4. These results indicate that the damage, given by S_v (macrocrack surface area per unit volume), increases with stress (Fig. 2), stress duration (Fig. 3), and alumina grain size (Fig. 4).

4. ANALYSIS

Figure 5 shows the idealized behavior of a crack. The upper limit for crack velocity is the Rayleigh wave speed, which is approached asymptotically as the stress intensity factor increases. An equation that represents well this behavior is:

$$V_c = V_r[\,1 - \exp\,(\alpha(K_I^2 - K_{IC}^2))\,] \qquad (1)$$

where V_c is the crack velocity, V_r the Rayleigh velocity, K_{Ic} the static fracture toughness, K_I the stress intensity factor at a crack velocity V_c and α a material parameter. It was possible to obtain the parameter α and therefore describe the dynamic crack propagation response for alumina. The Rayleigh wave velocity is approximately 90% of the shear wave velocity, which is given by (for alumina): $V_r = 0.9V_s = 5{,}640$ m/s. The static fracture toughness was taken as 4 $MPa.m^{1/2}$ for high-purity alumina. Suresh (3) measured the fracture toughness of alumina at a crack propagation velocity of approximately 1.2 km/s and he found a value of the order of 1.5 K_{Ic}, that corresponds to 6 $MPa.m^{1/2}$. Thus, the following equation describes the dynamics of crack propagation in alumina:

$$V_c = 5.64\,[\,1 - \exp(-1.2\times10^{-2}(K_I^2 - 16))\,] \qquad (2)$$

The model proposed herein is based on the ideas of crack nucleation, growth, and coalescence developed by the SRI-International group (4,5). It is assumed that the material has pre-existent flaws (voids, cracks, etc.) which are shown schematically in Figure 6 (a). Under dynamic loading, the material is submitted to the pulse illustrated in Figure 7, where the pulse changes from compression to tension and vice-versa, as the stress-wave progresses and reflects at interfaces between the aluminum and alumina.

Initially, under compression, some of the alumina pre-existing flaws are activated and grow through a stress and time-dependent mechanism, generating initial cracks. When tension is subsequently applied, growth of the initial cracks takes place at the velocity dictated by Figure 5, while subcritical flaws are activated in a time-dependent mode. The initial pre-existing flaws per unit volume is N_i. When the compressive pulse passes, the pre-existing defects are enlarged and new defects are created. Therefore, the population of flaws changes from N_i to $N_i + N_v$ as illustred schematically in Figure 6(a) and 6(b). N_v represents the additional number of flaws appearing as a result of the passage of the compressive stress pulse. Hence, N_v will be a direct function of σ_c (compressive stress level) and t (time of pulse duration). One assumes as a first approximation that:

$$N_v = N_i + t\sigma_c\dot{N}'_v \qquad (3)$$

The symbol $\dot{N}'_v$ represents the nucleation rate of flaws under compression. It is worth pointing out that the alumina grain size strongly affects N_i since the grain boundary is a place of existing microflaws which are formed as a result of anisotropy in alumina.

The tensile pulse follows the compressive one, and high velocity crack propagation (according to Eqn. 2) takes place for all cracks possessing critical size, as predicted by the fracture mechanics. As illustrated in Figure 6 (c), the crack population is divided into two groups, immediately after the transit of the compressive pulse. The first group contains cracks having at least the critical size or bigger, and the second one involves all cracks smaller than a_c. Beyond a_c the cracks grow with velocity V_c. Below a_c slower critical crack growth takes place, and these subcritical cracks may become critical within the time of pulse duration. Then one can write that:

$$N_v = N_v^c + N_v^{sc} \tag{4}$$

where N_v^c and N_v^{sc} are the number of flaws with critical and subcritical size per unit volume, respectively. Figure 6 (d) represents schematically crack intersections which give rise to fragmentation. Figure 8 illustrates the kinetics of fragmentation together with the representation of unloaded regions. The model incorporates the concept of unloaded fraction, since the available volume for crack nucleation and growth decreases as the time increases. The unloaded volume, V_u, can be obtained if one considers the pre-existing critical cracks, each one generating a small unloaded volume V'_u, as well as the critical cracks nucleated during the time of stress pulse application. So,

$$V_u = N_v^c V_o V'_u + \int_0^t V'_u + (V_o - V_u) dN_v^{sc} \tag{5}$$

where V_o is the total volume considered. Therefore, the unloaded fraction, f_u, is obtained as:

$$f_u = V_u/V_o \quad ; \quad df_u = V'_u N_v^{sc} (1 - f_u) dt$$

$$\int \frac{df_u}{1 - f_u} = V'_u N_v^{sc} \int dt \quad ; \quad -\ln(1 - f_u) = V'_u N_v^{sc} t + C$$

$C = -\ln(1 - N_v^c V'_u)$, for $t = 0$. So, $1 - f_u = \exp[At + B]$, where,

$$A = -V'_u N_v^{sc} \quad \text{and} \quad B = \ln(1 - N_v^c V'_u)$$

The crack surface generated by a critical crack is given by $S_c = 2\pi a_c^2$ and by $S = 2\pi a^2$ for a for a crack bigger than a_c. Then,

$$S - S_c = 2\pi (a^2 - a_c^2) \quad ; dS = 4\pi a da \tag{6}$$

It is necessary to find the time dependence of a, in order to express S as $S = f(t)$. This is done by considering Equation 1. So,

$$V_c = \frac{da}{dt} = V_r [1 - e^{-\alpha(\sigma_t^2 \pi a - \sigma_t^2 \pi a_c)}] \tag{7}$$

where σ_t is the tensile stress arising from compressive pulse reflection. By making $e^{\alpha \sigma_t^2 \pi a_c} = A'$ and $\alpha \sigma_t^2 \pi = B'$, one simplifies Equation 7 :

$$\frac{da}{1 - A' e^{-B'a}} = V_r dt. \text{ Integration leads to : } \int_{a_1}^{a_2} \frac{d\, e^{B'a}}{e^{B'a} - A'} = V_r \int_{t_0}^{t} dt$$

However one cannot integrate from a_c to a because $V_c = 0$ when $a = a_c$. An artifice has to be used, and the initial crack length is arbitrarily set at 1.1 a_c. One obtains:

$$a = \ln\left[(e^{1.1B'a_c} - A')e^{V_r(t-t_o)} + A'\right]/B' \tag{8}$$

As expected, this equation satisfies the boundary conditions, since $a = 1.1a_c$ when $t = t_o$ and $a \rightarrow \infty$ when $t \rightarrow \infty$

By taking the square of Equation 8, and differentiating, one obtains:

$$a^2 = \frac{1}{B'^2}\left[\ln(A' + e^{V_r t}\frac{e^{1.1B'a_c} - A'}{e^{V_r t}})\right]^2$$

By making, $\frac{e^{1.1B'a_c} - A'}{e^{V_r t_o}} = C$, one leads to:

$$dS = 4\pi a da = \frac{4\pi V_r}{B'^2}\left[\frac{\ln(A' + C e^{V_r t})}{A' + Ce^{V_r t}} e^{V_r t}\right]dt \tag{9}$$

The total surface area per unit volume is determined from the progression of cracking with time. Referring to Figure 6, one can calculate the fragmentation as a function of time by considering the following components:
a) Cracks that are critical at the onset of tension ($t = 0$):

$$S_{v1} = S_c N_v^c$$

$$S_c = 2\pi a_c^2 = \frac{2K^4}{\pi \sigma_t^4}$$

$$S_{v1} = \frac{2K^4}{\pi \sigma_t^4}\left[(N_i + t\sigma_c N'_v) - N_v^{sc}\right] \tag{10}$$

b) Increase in surface area of cracks that are critical at time 0 and that continue to grow during the time of pulse duration, t:

$$S_{v2} = N_v^c \int_0^t dS'$$

The growth rate of these cracks is slowed down by the unloaded material. To a first approximation:

$dS_{v2} = (1 - f_u)dS$. This leads to:

$$S_{v2} = \left[(N_i + t\sigma_c \dot{N}'_v) - N_v^{sc}\right] \frac{4\pi V_r c^B}{B'^2} \int_0^t \left[\frac{\ln(A' + Ce^{V_r t})}{A + Ce^{V_r t}} \cdot e^{V_r t}\right] dt \tag{11}$$

c) The third component of the surface area per unit volume are the cracks that become critical during the time interval from 0 to t. A nucleation rate $\dot{N}_v^c$ of critical cracks is defined and assumed to be constant. It is assumed that no nucleation takes place in unloaded material. Thus:

$$S_{v3} = S_c \int_0^t \dot{N}_v^c (1 - f_u)\, dt$$

$$S_{v3} = \frac{2K^4}{\sigma_t^4}\left[\frac{(1 - N_v^c V'_u)(e^{N_v^{sc}} - 1)}{V'^2_u e^{N_v^{sc}}}\right] \tag{12}$$

d) The fourth component of fragmentation is provided by the growth of cracks that become critical during the time interval from 0 to t. This involves growth of different cracks for different lengths of time, since each critical crack has a specific nucleation time.

$$S_{v4} = \int_{t'=0}^{t'=t} (1 - f_u) N_v^{sc} (1 - f_u) dS$$

$$S_{v4} = \frac{4\pi V_r c^{2B} N_v^{sc}}{B'^2} \int_{t'=0}^{t'=t} \frac{e^{(2A + V_r)t} \ln(A' + Ce^{V_r t})}{A' + Ce^{V_r t}} dt \tag{13}$$

Therefore, the total crack surface area per unit volume is found by summation of the four contributions (Eqns. 10, 11, 12, and 13):

$$S_v = S_{v1} + S_{v2} + S_{v3} + S_{v4} \tag{14}$$

One sees that S_v is a function of stress-wave parameters σ_c, σ_t, t, as well as material parameters N_i, N_v^c, N_v^{sc}, N'_v, N_v^{sc}, K_{Ic}, α. By independent experiments it is possible to establish these parameters which can, when inserted into Equation 14, predict the fragmentation parameter S_v. There are many simplifying assumptions in the model, but it is thought that it incorporates the principal events in plane stress wave induced damage.

Andrade (6) considered the pre-existing defects concentrated primarily at the alumina grain boundaries as a result of its anisotropy. He did simplifications in the model and he showed reasonable correlation between experimental and predicted damage in alumina and it is shown in Figure 9, where damage is plotted against grain-size and pulse duration, respectively in Fig. 9 (a) and 9 (b).

REFERENCES

1. D. Yaziv, "Shock Fracture and Recompaction of Ceramics", Ph.D. thesis, Dayton University, Ohio (1985).

2. L.H.L. Louro, "Stress-Wave Induced Damage in Alumina-Based Ceramics", Ph.D. Thesis, New Mexico Institute of Mining and Technology, New Mexico (1988).

3. S. Suresh, J. Duffy, K. Cho, and E. R. Bopp, J. Eng. Matls. Techn., Trans. ASME, (1988).

4. D.R. Curran, D.A. Shockey, and L. Seaman, J. Appl. Phys.,44(1973)4025.

5. L. Seaman, D.A. Shockey, and D.R. Curran, J. Appl. Phys.,47(1976)4814.

6. J.R.A. Ribeiro, "Fratura Dinamica em Alumina de Alta Pureza", Tese de Mestrado, Instituto Militar de Engenharia (IME), Rio de Janeiro, RJ, Brasil (1991).

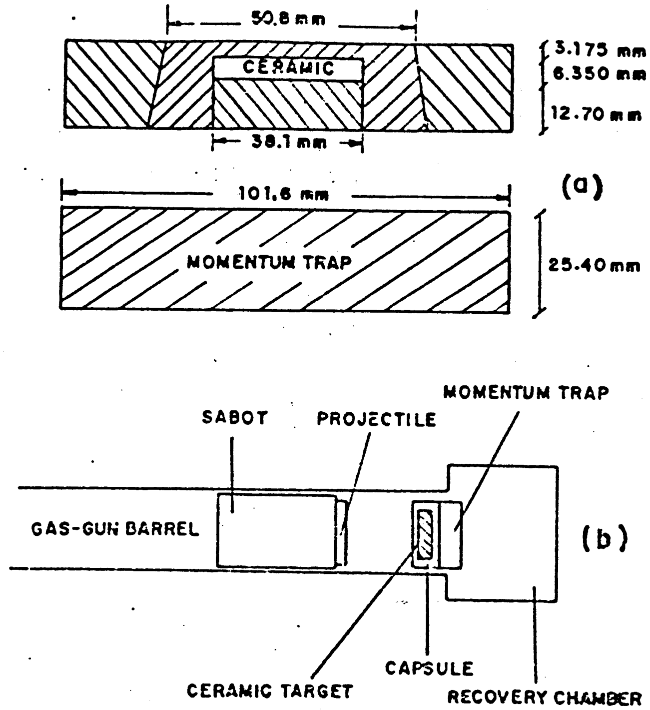

FIGURE 1

Schematic representation showing :
(a) Capsule design;
(b) Capsule and projectile inside the gas gun.

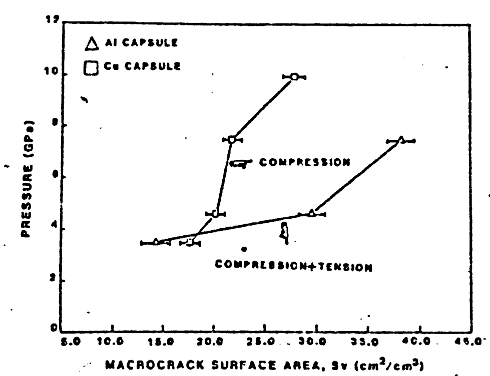

FIGURE 2

Damage in alumina as a function of stress.

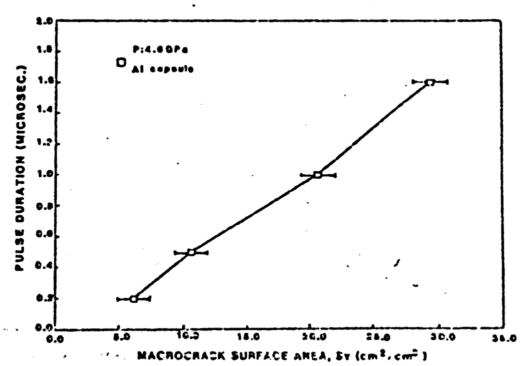

FIGURE 3

Damage in alumina as a function of pulse duration.

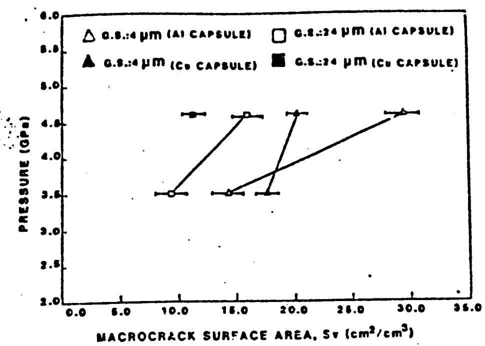

FIGURE 4

Alumina damage as a function of grain size.

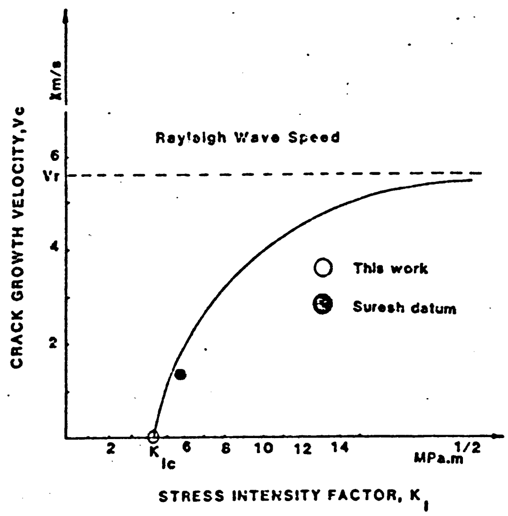

FIGURE 5

Crack velocity as a function of stress intensity factor for alumina.

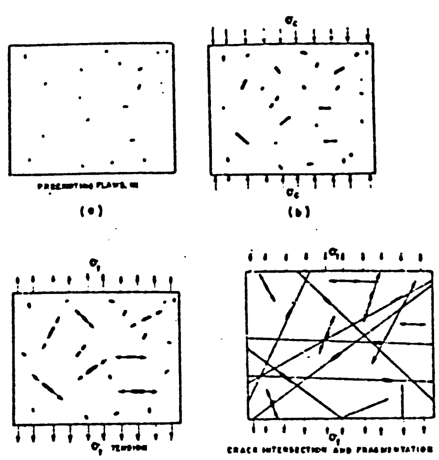

FIGURE 6

Schematic representation:

(a) ceramic "as-received" with inherent flaws;
(b) flaw increase due to compression;
(c) critical and subcritical flaws under tension;
(d) crak intersection and fragmentation.

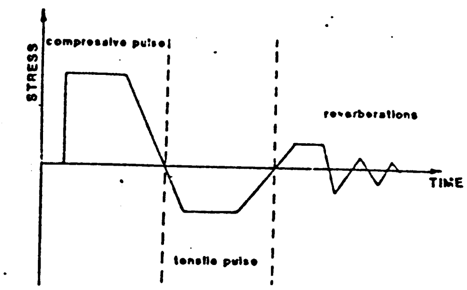

FIGURE 7

Stress-wave pulse profile impinged to the ceramic.

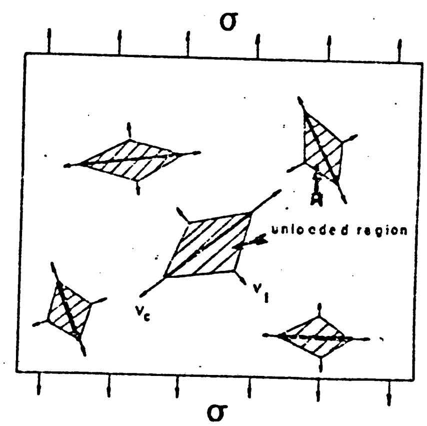

FIGURE 8

Schematic representation showing the kinetics of fragmentation.

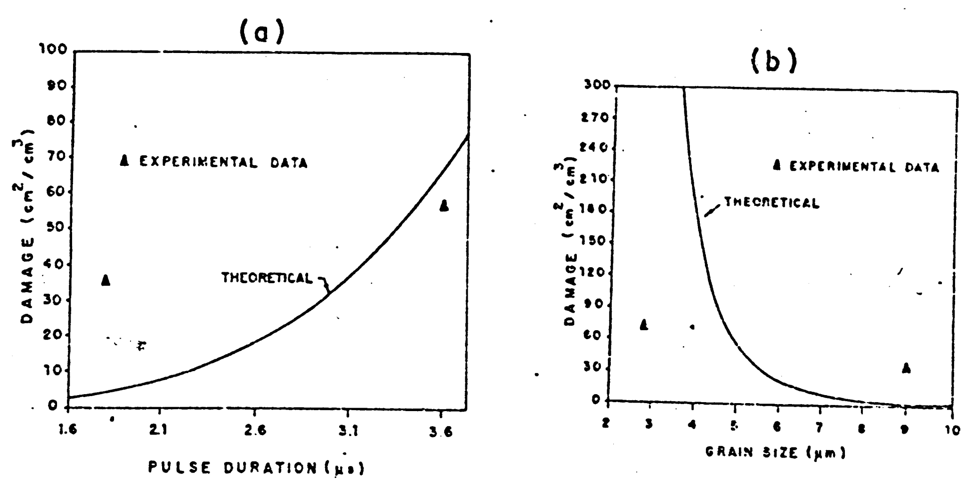

FIGURE 9

(a) Model prediction of damage as a function of pulse duration.

(b) Model prediction of damage as a function of grain size.