BRITTLE PLATE FAILURE UNDER IMPACT EFFECT

A.I. SADYRIN

Research Institute of Mechanics,
University of Nizhny Novgorod,
Nizhny Novgorod, Russia

ABSTRACT

In order to describe the condition of a brittle medium with defects, functions $N_0(x,t)$ and $N(x,r,t)$ are introduced which characterize the total quantity of crack-like defects within a unit volume and distribution of defects with respect to sizes within the same volume, respectively. Based on some experimental and theoretical evidence, evolution equations were formulated for N_0 and N . The model obtained predicts, depending on the impact velocity, the plate failure modes related with formation of conical and radial cracks, diffusion failure zones or failure front formation.

KEYWORDS

Impact loading, microcracks, crack growth velocity, cleavage failure, radial and circumferential cracks, brittle fracture.

INTRODUCTION

An ever growing use of rigid brittle materials in modern technologies (combined protective elements, protective and insulating coatings, etc.) favours interest towards studying the events of deformation and failure of such materials under different load conditions including the range of intense impact effects. It has to be noted that a relatively insufficient knowledge of the processes of an intense impact deformation of brittle targets has to do with peculiarities of their failure. The failure of low-plasticity targets brings about pronounced fragmentation of material at the impact site, brittle barrier is frequently observed to fail entirely in the course of experiment which restricts to a large extent the activity with the purpose to investigate residual target shapes. Brittle fracture is known to be intimately related with complicated processes of fast crack nucleation and propagation mechanics, sensitive to surface condition, various defects, inhomogeneities, concentrators impeding experimental and theoretical study of the brittle fracture events. Among the most important events, from the viewpoint of fracture mechanics, observed in the experiments on impact failure of low-porosity brittle materials (ceramics, glass, etc.) one can mention the following.

Under the effect of a uniaxial impact deformation the existence of a limit compression stress was revealed which is similar to Hugoniot-elastic limit (σ_{HEL}) such that in materials compressed exceeding σ_{HEL} partial or complete strength drop was observed in the case of tension to follow (Gust and Royce, I97I; Rosenberg et al. I989). Failure of brittle materials occurs without noticable residual strains such that compressive strength is much more than tensile strength and failure is recorded with a certain time delay on reaching the limit state (Zilberbrand et al. I989; Coble and Parikh, I972). Under intense impact loads a multi-site crack nucleation and growth is registered and the cracks are usually known to propagate with high velocity comparable with that of elastic shear waves. The crack growth velocity dependences on the dynamic stress intensity factor (SIF) obtained experimentally for a group of brittle materials are well approximated by a Γ-shaped dependence (Kalthoff et al., I977; Kobayashi and Dally, I977). Fig. I depicts such experimental curves for araldite and KTE epoxide.

To analyse dynamic failure in applied problems of the class under consideration the most preferable is an approach based on the concepts of microstatistical fracture mechanics (Curran et al.,I987) making use of additional parameters of state. Kinematic equations for the additional parameters in this case are phenomenological on the whole, though some familiar specific features of mathematical and physical failure models are usedat their formulation stage.

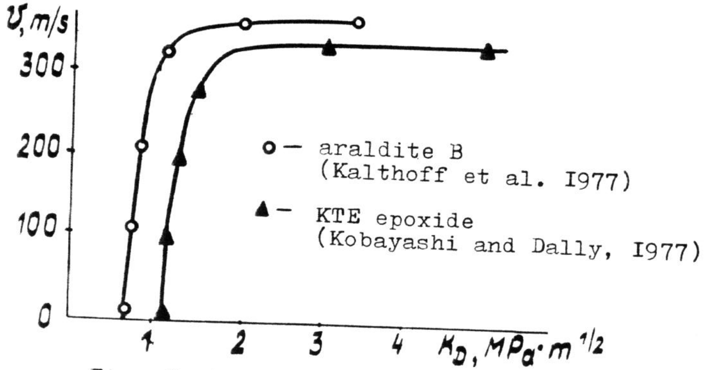

Fig. I. Crack growth velocity.

FAILURE MODEL

First of all present schematically the results with respect to conditions of the crack start and growth velocity in brittle solids for a combined stressed state (axisymmetric and plane deformations). In analytical solutions arrived at within the framework of the Iinear Fracture Mechanics (LFM) many common features were observed concerning the laws of start and dynamic propagation of individual cleavage and shear cracks characterized by the SIF K_I and K_{II} under canonical forms of the stressed state (Freund, I986). The growth of the transverse shear crack, however, under the effect of compressive stresses normal to the crack edges is accompanied with a group of effects due to the sliding friction forces of the crack edges with respect to each other. A detailed pattern of the stress distribution within the sliding zone is rather complicated (Goldstein and Zhitnyakov, I99I),but, schematically, the effect of compressive stresses can be reduced to the following. First, singularity due to tangent stresses alone remains at the crack tip. Second, the value of effective shear stresses is reduced and can be estimated as

$$\tau_{eff} = \tau + \mu\sigma_1 \qquad (I)$$

where μ is the sliding friction coefficient and σ_1 is compressive stress of the crack edges. Third, irreversible processes of the energy dissipation under friction reduce the effective energy release rate in the course of the crack travel. This agrees with experimental observation concerning the ordering effect of compressive stresses while the crack start condition with account of (I), accepted within the LFM, is expected to lead to a familiar strength criterion for brittle materials $\tau + \mu\sigma_1 < \tau_* = K_c/(\pi r)^{1/2}$. The reasoning suggested implies a feasible way to extend the crack start conditions over to the arbitrary types of the stressed state with the help of generalized strength criteria.Such a criterion of strength for structurally inhomogeneous materials taking into account the presence of crack-like defects in a solid and brittle failure can be formulated as follows

$$\sigma_e = \varkappa\sigma_i + (1-\varkappa)\sigma_1 A^{1-I} < \sigma_p \qquad (2)$$

Here σ_i and σ_1 are stress intensity and maximal principal stress, respectively, $\varkappa = \sigma_p/\sigma_c$ where σ_p , σ_c are tensile and compressive strengths, $A < 1$ is material inhomogeneity parameter, I is rigidity factor of the stressed state,

$$I = (\sigma_1 + \sigma_2 + \sigma_3)/\sigma_i$$

In accordance with (3) we assume that to start a crack of radius $r > r_0$ the following LFM condition has to be satisfied

$$K_s = \sigma_e(\pi r_0)^{1/2} \qquad (3)$$

where K_s and K_c is static value of the SIF and static cracking resistance. Making use of the approximation relationship of the dynamic SIF values K_D with K_s , crack growth velocity v and Rayleigh wave velocity v_*

$$K_D = K_s(1 - v/v_*)^{1/2} \qquad (4)$$

and Γ-shaped approximation of $v(K_D)$, one can write the crack growth velocity with account of (3) as follows

$$\dot r = \begin{cases} v_*(1-a/r); & v \le v_\ell, \ r \ge r_0 \\ v_\ell; & v > v_\ell, \ r \ge r_0 \end{cases} \qquad (5)$$

Here $a = (K_c/\sigma_\ell)^2/\pi$, v_ℓ is a limit crack velocity under a Γ-shaped approximation and $\dot r$ =0 for $r < r_0$. The expression (5) lends itself easily to integration and can be extended to more complicated dependences $v(K_D)$.

Among parameters describing the damaged medium condition within the frames of microstatistical fracture mechanics one can mention the value of microcrack concentration N. For high stresses, moderate temperatures and insignificant plastic strain values the exponential form of kinetic equation for N can be taken (Curran et al., 1987)

$$\dot N = \dot N_0 \exp[(\sigma_\ell - \sigma_0)/\sigma_{01}], \quad \sigma_\ell > \sigma_0 \qquad (6)$$

where $\dot N_0$, σ_0, σ_{01} are material constants. The equation describing microcrack nucleation has to be complemented with a function of initial distribution of emerging defects with respect to sizes and the subsequent distributions will be governed by the microcrack growth equation (5). Good approximation of such a function was obtained in a work by Curran et al. (1987)

$$N = N_0 \exp(-r/r_1) \qquad (7)$$

where N is a number of microcracks with radius exceeding r per unit volume, N_0 is a number of microcracks of all sizes within the same volume, r_1 is distribution parameter. Fig. 2 borrowed from a work by Curran et al. (1987) depicts experimental curves for distribution of microcracks N with respect to sizes in ceramic plates under the impact by spheric tungsten carbide particles with different velocities v_i.

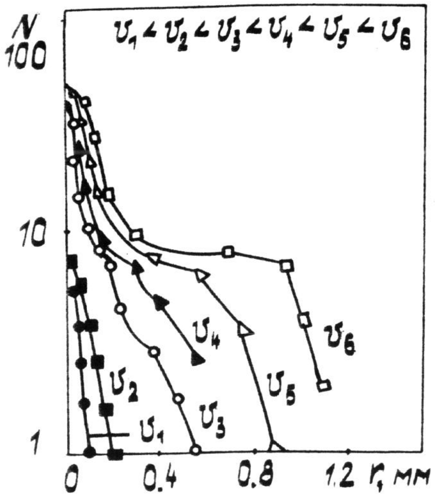

Fig.2. Distribution of cracks with respect to sizes (Curran et al., 1987)

From the curve form it follows that final distributions of N for low impact velocities v_1 and v_2 correspond mainly to microcrack nucleation (growth of N_0) and are well approximated by the expression (7). At higher velocities of impact microcrack size increase is observed together with microcrack nucleation, this size growth being only the case for some longest microcracks. The distribution in this situation offers a

smooth transient zone connecting the sizes of non-increasing and intensively increasing cracks. The observed ceramics failure events are in fair agreement with equations of microcrack nucleation and growth (2), (5)-(7) suggested in this paper. As parameter governing the strength of a brittle medium with microcracks we take an integral volume of microcracks within a unit volume continuum element

$$V = \kappa \int_0^{r_\kappa} r^3 \, dN \qquad (8)$$

Here r_κ is a maximal radius of microcracks in a distribution $\kappa = 0.1\pi$ is a constant characterising the volume of a unit radius microcrack.

NUMERICAL RESULTS

The pattern of impact interaction between a brittle plate and a projectile - a cylindrical elastoplastic rod - is depicted in Fig.3. The axes z and r correspond to the axial and radial coordinates, respectively. Before collision the projectile and the target are supposed to be undeformed and surface tractions are active within the contact area, only. The first stage of the plate failure process under different collision velocities v_i is shown in Fig.4 where to the four values of the impact velocities there correspond four columns with three subsequent failure conditions.

At low impact velocities failure within the plate was observed to follow the pattern given in the left-hand column. On the face surface of the plate circumferential fracture is seen to initiate propagating into the plate as a cleavage crack. The clearly localized crack contour outlines the so-called fracture conoid in the plate. As the impact velocity increases, the crack contour gets blurred by additional fracture and fracture as a whole begins to acquire diffusive nature (two middle columns in Fig.4). The fracture in the cases considered above is attributed mostly to the emergence of tensile stresses within the zone of interaction between the stress waves.

At high impact velocities fracture within the plate is observed to start exactly in a direct compression wave with forming a failure wave front which can be described as a finite thickness zone of transition from virgin material to the damaged one. The compressive stresses in the direct wave exceed σ_{HEL} in this case.

More advanced stages of failure evolution are given schematically in Fig.3. At low impact velocities the circumferential fracture zone (line L_1) reaches the rear plate surface completing, thereby, the formation of the fracture conoid. On reflection of the compressive wave from the rear surface, fracture can be observed near the rotation axis (shaded). This fracture forms a network of radial cracks dividing the plate into several circular sectors. Propagation of fracture within the conoid and its interaction with unloading waves results in

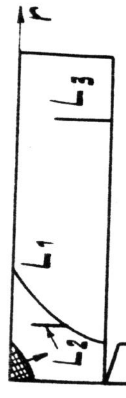

Fig.3. Impact pattern.

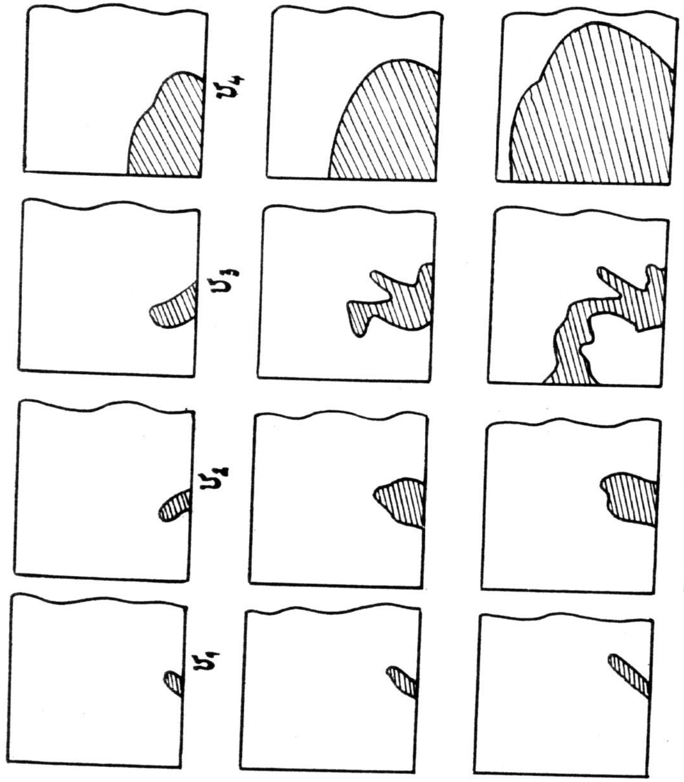

Fig.4. Initial stage of plate failure depending on impact velocity ($v_1 < v_2 < v_3 < v_4$).

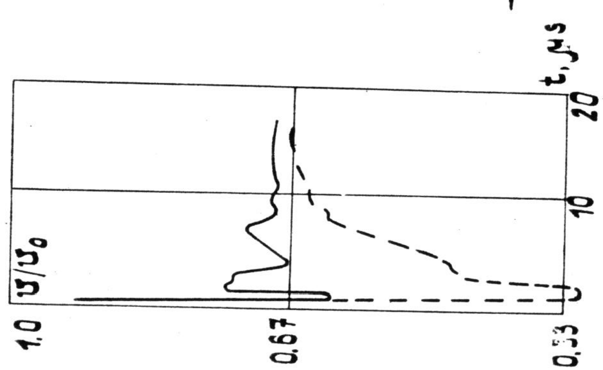

Fig.5. Speed of rod penetration into a brittle barrier.

a complete fragmentation of target material. Within rather a narrow range of collision velocities under the unloading wave incidence from the rear plate surface onto the tip of a moving circumferential crack, branching of the crack can be observed (line L_2 in Fig.3). The hypotheses on a restricted range of the stressed state parameters within which the crack branching can be expected were discussed previously (Vasil'yev et al., 1990).

Under certain impact velocities formation of cracks marked with a L_3 line was observed. This type of failure is also caused by interaction of waves - direct shear wave and longitudinal wave reflected from the lateral plate surface. Numerical results were compared with experimental evidence (Pugachev et al., 1988) to show qualitative and fair quantitative agreement.

Indirect comparison between predicted and experimental data with respect to high impact velocities is given in Fig.5 where speed variations for the projectile penetration into a barrier under brittle fracture are presented. A solid line is for the model of instantaneous material failure when condition (2) is violated while a dash line is drawn for models (2), (5)-(8). Finite time necessary for the failure front to form leads to a significant decline of penetration speed at the initial stage in the latter case. A steady-state penetration speed, however, corresponds to penetration into material of the barrier with strength lost. Such effects of penetration speed variation were observed experimentally (Zilberbrand et al., 1989).

REFERENCES

Coble R.L., Parikh N.M. (1972) Failure of polycrystalline ceramics. In: Fracture (H.Liebowitz), V.7, P.221-299, Mir, M. (in Russian)

Curran D.R., Seaman L., Shockey D.A. (1987) Dynamic failure of solids. Phys.Rep.; Rev.Sect.of Phys.lett. V.147, N.5-6, P.253-383.

Freund L.B. (1986) Crack propagation in solids. In: Comp.Meth in the Mech.of Fract.(S.N.Atluri) V.2, P.83-128, North-Holland Amsterdam. New York. Oxford. Tokyo.

Goldstein R.W., Zhitnikov V.Yu. (1991) Analysis of crack surface sliding process taking into account friction forces under complex loading. Izv. AN SSSR MTT N 1, P.139-148 (in Russian)

Gust W.H., Royce E.B. (1971) Dynamic yield strength of B_4C, BeO and Al_2O_3 ceramics. J.Appl.Phys. V.42 N.1, P.276-295.

Kalthoff J.F., Beinert J., Winkler S. (1977) Measurements of dynamic stress in beam specimens. In: Fast Fracture and Crack Arrest (G.T.Hahn, F.M.Kanninen) ASTM STR 627 P.132-161, ASTM, Baltimore.

Kobayashi T., Dally J.W. (1977) Relation between crack velocity and stress intensity factor in birefringent polymers. ibig. P.257-273.

Pisarenko G.S., Lebedev A.A. (1976) Deformation and strength of materials under complex stressed state. Naukova dumka.Kiev (in Russian)

Pugachev G.S., Sadyrin A.I., Sinani A.B. (1988) Experimental and theoretical investigation of brittle plate impact fracture. In: Prikladnyye problemy prochnosti i plastichnosti. Gorky univer. P.35-47. (in Russian)

Rozenberg Z., Bless S.J., Brar N.S. (1990) On the influence of the loss of shesr strength on the ballistic performance of brittle solids. Int.J.Impact Eng. V.9, N.I, P.45-49.

Slepjan L.I. (1990) Mechanics of crack. Sudostroyeniye. Leningrad (in Russian)

Vasil'yev A.D., Samelyuk A.V., Firstov S.A. (1990) Crack branching in brittle materials. In: Mekhanika i fizika razrusheniya khrupkikh materialov.P.89-95, Inst. PM AN USSR. Kiev (in Russian)

Zilberbrand E.A., Zlatin N.A., Kozhushko A.A., Polozenko V.I. Pugachev G.S., Sinani A.B. (1989) On the mechanism of interaction between plastic projectile and brittle rigid barrier. J.of Techn.Phys. V.59, N.IO, P.54-58 (in Russian)