ANALYSIS OF FRACTURE PROCESSES UNDER DYNAMIC LOADING

A.I. ROUZANOV

Research Institute of Mechanics,
Nizhny Novgorod State University, Russia

ABSTRACT

The paper presents models used to analyse the fracture processes under dynamic loading at different stages. At the accumulation stage of scattered defects, damage is represented as the nucleation, growth and coalescence processes of pores or microcracks. Spallation phenomena in copper are analyzed, and some peculiarities of micropore nucleation, growth and coalescence processes are tackled. The applicability of the Split Hopkinson Bar (SHB) method for determining the dynamic cracking resistance of materials is assessed using the numerical analysis. The problem of a double-layer plate perforated by a rigid penetrator is solved with analysing both the damage accumulation stage and the target debris dispersion stage.

KEYWORDS

Dynamic loading; nucleation, growth and coalescence of pores or microcracks; dynamic crack resistance; failure on impact

INTRODUCTION

Experimental investigations on a variety of materials, such as metals, rocks, polymers, showed that failure under dynamic loading is a multistage process including nucleation, in the region of minimum strength and maximum stress, of numerous microdefects (micropores, microcracks, adiabatic shear bands), their growth, coalescence and, finally, cleavage and disintegration of the material through the formation of one or more macrocracks or through crushing. Depending on the nature of the material and the loading conditions, the characteristic times of crack formation and crushing may vary and influence the total structure life. In any case, some finite time interval which depends on the stress-strain history is needed to complete failure. It is conventional to divide this time interval into three stages, namely, nucleation of microcracks, their coalescence into a macrocrack and propagation of this macrocrack. Mechanisms of these stages are different and should be described using different approaches. The first two stages are investigated using the continuum damage mechanics. The aim of the present paper is to discuss the above problems for the materials subjected to dynamic loading, including shock loading.

DETERMINATION OF DYNAMIC FRACTURE RESISTANCE

In structures designed to be economically reasonable one generally cannot avoid the possibility of crack growth initiation, yet any uncontrolled crack growth is to be eliminated. To this end, special measures should be taken providing for the arrest of a rapidly growing crack. The final stage of failure, the propagation of the macrocrack, is the most thoroughly studied one, using the Griffith approach and the linear fracture mechanics based on the stress intensity factor (SIF). Further development of the approach was to introduce the notion of the energy flow to the crack tip in the form of the Rice-Cherepanov integral where the critical value of the invariant integral is used as the failure parameter. The situation is less clear in the case of cracked bodies under pulsed loads. For quasi-brittle failure, the dynamic energy release rate can be directly related to the value of J-integral or the dynamic SIF. The possibility of crack initiation can be predicted through comparing the fracture resistance K, corresponding to the case of a propagating crack with the dynamic SIF. The dynamic SIF values can be measured using different experimental approaches. A version of the Split Hopkinson Bar (SHB) method (Klepaczko 1979, 1984) may be effective for the case of loading by stress waves. In this method, a modified standard compact specimen (1) with a crack is placed between a supporting bar (4) and a transmitting bar (3) which is loaded by impact (the numerical numbers are the designation of the component of the experimental set-up shown in Fig.1). The transmitting bar has a wedge (2) attached to it. Transducers (5) and (6) measure strains of the incident, reflected and transmitted pulses, which then are used to determine the dynamic fracture resistance. The impacting rod should be about 10 times longer than the specimen; then the loading process of the specimen by the incident wave through the wedge can be considered as quasi-stationary. Another assumption used is the solution for the elastic waves without dispersion. In the dynamic loading, the time to failure is relatively short, there are inertia forces acting upon the specimen, so the fracture resistance analysis that takes no account of these effects may lead to some error. In this connection, numerical simulation of the wave propagation processes in a system consisting of a tested specimen, a loading bar, and a supporting bar in a 2D configuration could be of interest. The results of the analysis of such a problem are given below. Geometry of the bars contacting with the specimen corresponds to Fig.1; the compact tension specimen was replaced by a disk specimen

with a V-notch and a fatigue crack in the analysis. The left end of bar (1) was loaded by a pressure pulse such that only elastic waves propagated through it. The results of the analysis are shown in Figs.2 and 3, where time (t) is in microseconds. The curves in Fig.2 depict the variation of strains in the transmitted, incident and reflected waves, respectively. Fig.3 illustrates the wave propagation dynamics, showing the longitudinal stress history (the upper curve) and the velocity history for the points near the loaded ends. Initially, the compressive stresses increase with the applied load. Then, at about two run times of the wave along the rod, the wave reflected from the end A arrives at this point, the stresses become tensile and then drop to zero. Displacement of the points of the disc specimen begins when the wave reaches the rod end A. When the compressive wave reaches the end A, the reflected wave is a tensile one and the point velocities approximately double (Fig.3). In some time the wave, reaches the end B of the supporting bar and in several runs of the wave, the point velocities of the end B become equal to those of the disk specimen near the end A. As far as the changes of strains in the transmitted wave are concerned, for ductile materials this pulse has a smeared profile, and for the more brittle and rigid materials the profile is steep, with a sharp fall. Such computations make it possible to evaluate the longitudinal and transverse accelerations due to the wedge motion and to consider the possibility of determining the characteristic dynamic crack resistance of materials using the specimens that differ from the standard compact specimen.

DEVELOPMENT OF MODELS AND ANALYSIS OF SCATTERED DEFECT ACCUMULATION

The incubation stage of the defect accumulation may take a considerable part of the total life, preceding the propagation stage of the main crack or disintegration of the body to debris. The development of the notions describing failure as the process of defect nucleation, growth and coalescence (Seaman et al., 1976) seems promising in describing this stage. Based on this investigation, the failure models accounting for the pore or microcrack nucleation, growth and coalescence were developed in the works of A. I. Rouzanov (1980, 1981, 1985). The consist of two parts: relations describing the laws of defect nucleation, growth and coalescence; and constitutive equations determining the elastoplastic behaviour of the material accounting for the stress relaxation and the changes in the mechanistic characteristics due to the defect nucleation and growth. The nucleation and growth processes of a large number of defects are described by introducing the distribution functions for micropores or microcracks according to such parameters as size, orientation, and center coordinates. The behaviour of the materials with defects where failure follows the mechanism of pore nucleation and growth is described using the plasticity theory of the porous media. Deformation of the porous materials is analysed taking account of the displacements (Rouzanov, 1980, 1985). The description of the material behaviour with the defects in the form of planar microcracks is based on the analysis of the uniformly distributed but differently oriented in the analysed volume, microcracks, including anisotropy due to their nucleation and growth (Rouzanov, 1981). The description is illustrated by the analysis of the crack nucleation, growth, and coalescence processes during the planar impact of two copper plates with the impact velocity of 186 m/s (Fig. 4). The back surface of the target plate is backed by a material with a lower acoustic stiffness, PMMA. Such a configuration is widely used in the experimental investigations of the dynamic fracture. The results of the analysis are shown in Figs. 5 to 7 in comparison with the experimental data (Johnson, 1981). Fig. 5 shows the histories of the volume fraction of pores and also the stresses on the spall surface (the spall surface was taken to be the surface of maximum damage. In Fig. 6, the axis of abscissae measures time, and the axis of ordinates shows the axial stress at a point 0,5 mm away from the interface between the copper and PMMA. The stress measured by a manganin gauge is designated by (2) and the numerical results by (1). The wave of compressive stresses arising during the impact is reflected by the copper/PMMA interface and, on interaction with the unloading wave running from the free surface of the incident plate, a region of tensile stresses is generated in the specimen. These tensile stresses result in the process of pore nucleation and growth. The increase in the pore concentration is accompanied by unloading the material in the region of the growing cavities, which results in propagating the perturbation. The increase of stress in about 0,9 microsec (Fig. 6) is explained by the arrival of the perturbation, generated by the nucleation and growth of the pores in copper, at the copper/PMMA interface. Fig. 7 shows the pore volume fraction through the specimen thickness; the experimental data are shown by circles. Generally, the numerical results are in good agreement with the experimental data both for the stresses and the pore volume fractions, which may be considered to be the confirmation of the model used.

The importance of the studies on dynamic fracture is concerned not only with the prediction of failure regions, but also the number of fragments, their size, velocity and trajectory. The failure process can be traced down to the fragmentation, and the further behaviour of the fragments can be predicted using the models accounting for the nucleation, growth and coalescence of defects (pores, microcracks, adiabatic shear bands). The number and the size of the fragments are determined in this approach by the defect distribution kinetics. Yet, in the absence of data on the defect coalescence kinetics, the use of such models is impeded, and some simpler energy based approaches are usually used that do not account for the defects in the explicit form. Such problems require the development of the numerical procedures that allow one

to account for the failure processes up to the disintegration of the body into fragments. One of such methods is the finite difference scheme with the variable node connectivity. To illustrate the implementation of the approach, the numerical analysis of the oblique impact of a rigid cylindrical projectile (velocity of 6km/s) on a double-layer target (a plane strain problem) was carried out. Fig. 8 shows the sequence of the target perforation process. Initially, high compressive stresses develop in the target. The longitudinal shock propagates through the target thickness and first reaches the back surface of the target. Then a tensile wave arises bringing about failure of the target, which results in the formation of a debris cloud oriented primarily in the normal direction to the target. Meanwhile, the projectile keeps moving in the direction close to the impact direction, which results in the formation of debris with the primary velocity direction of about 45 . At about 15 microseconds the projectile completely perforates the plate. Thus, the present approach makes it possible to describe the two stages of the scattered defect accumulation and also the disintegration of the body into fragments.

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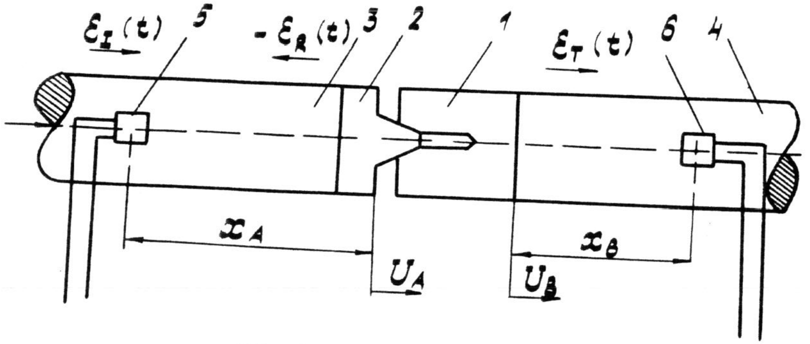


Fig.I. Experimental configuration.

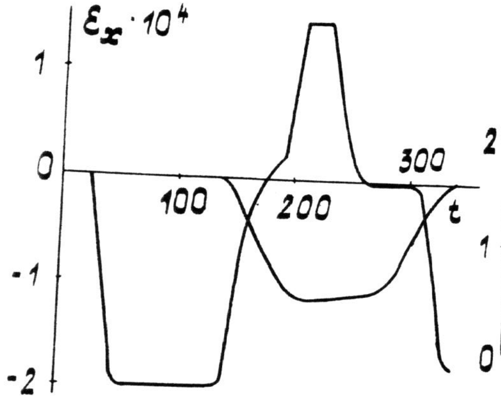
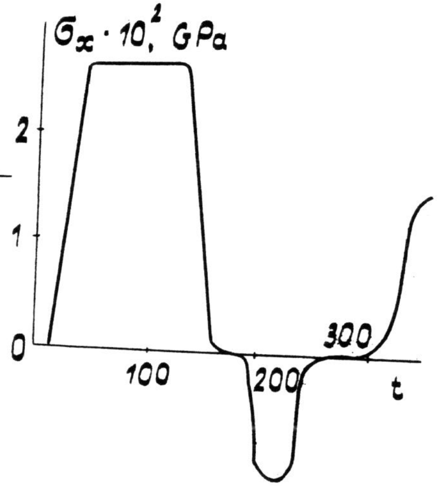


Fig.2. Strain histories.



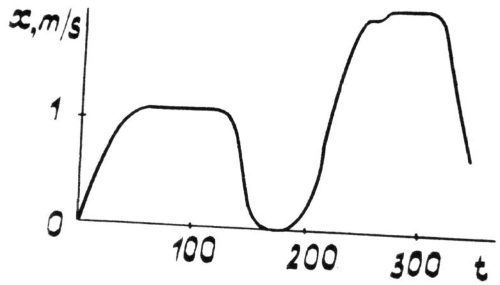
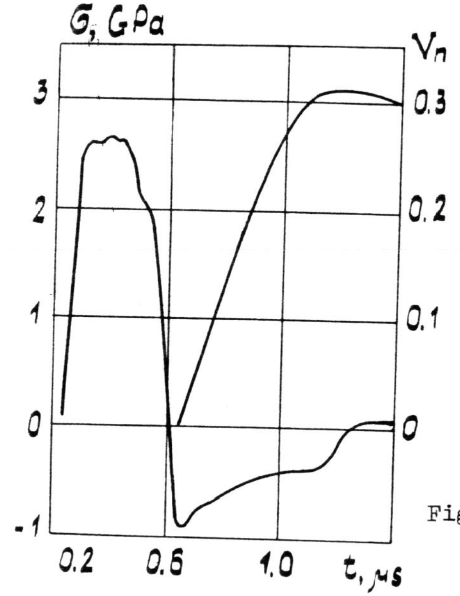


Fig.3. Longitudinal stress and velocity histories.



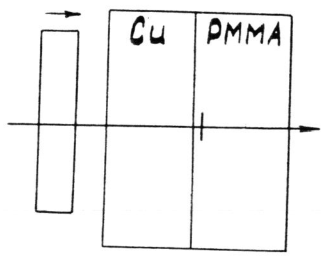
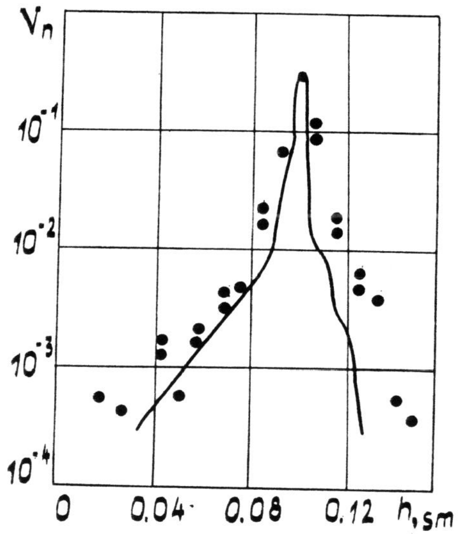


Fig.4. Loading configuration.

Fig.5. Stress and damage histories in the spall plane.



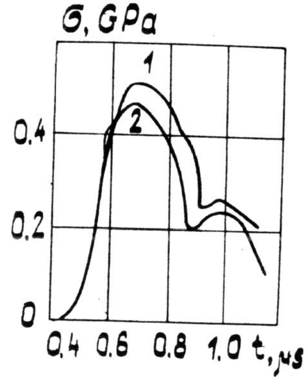


Fig.6. Stress histories at the interface.

Fig.7. Pore volume distribution through the specimen thickness.

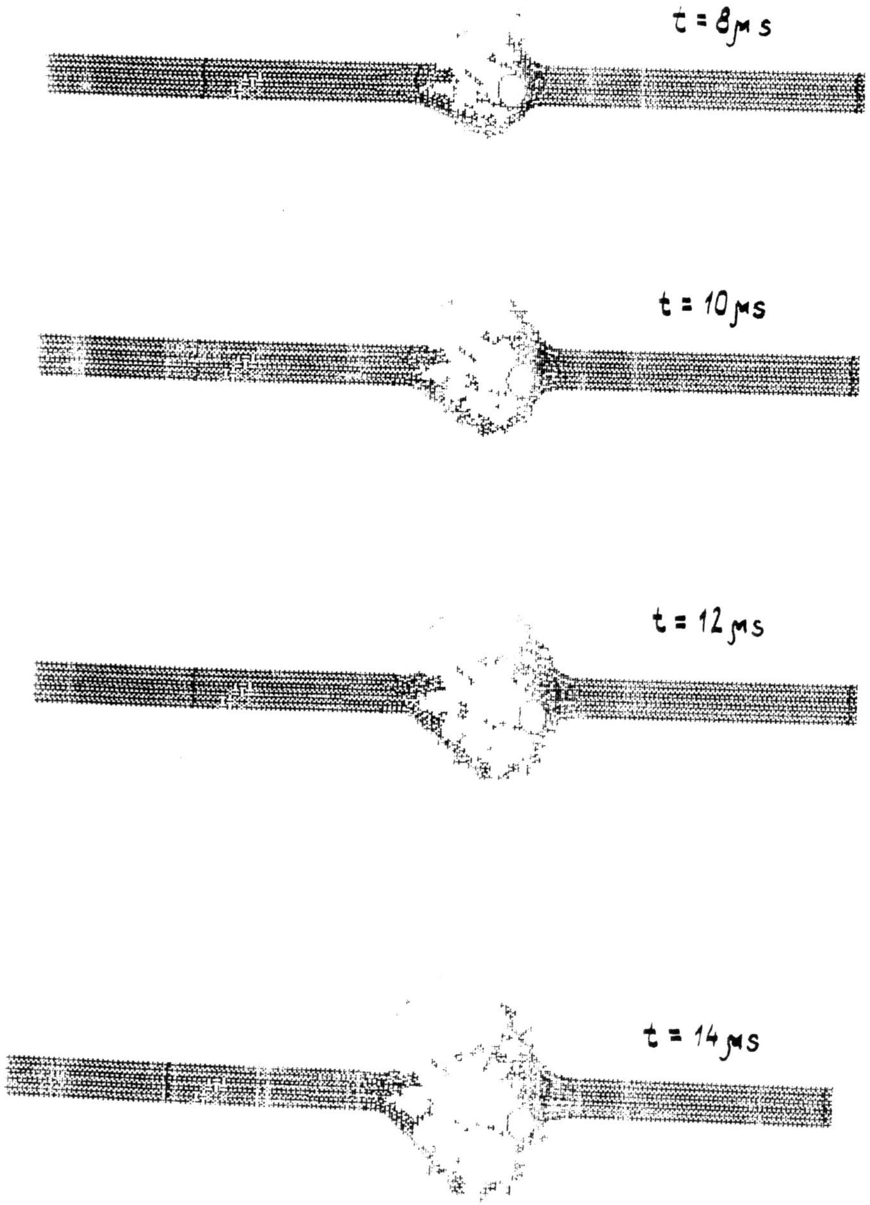


Fig.8. Perforation process.