DISTINCTIVE FEATURES OF FRACTURE PROCESSES IN BERYLLIUM UNDER IMPACT LOADING

V. K. Golubev and I. R. Trunin

We present the results of numerical analyses of the conditions of cleavage fracture of beryllium under impact loading performed for the cases of a fixed value of cleavage strength and of the kinetic description of fracture processes according to the model of initiation and growth of damage. It is shown that the results obtained by using fixed values of the cleavage strength of beryllium agree fairly well with the experimental data.

The cleavage strength of beryllium (one of the most important materials for nuclear and spacecraft engineering) under impact loading was studied in numerous works. Thus, Christman and Froula [1] established the time dependence of the cleavage strength of high-purity coarse-grained beryllium at normal and elevated temperatures (up to 260°C) by the method of metallographic analysis. As a result of elastoplastic calculations, it was shown that, for typical durations of loading pulses of 0.3-1.0 μsec, the values of cleavage strength corresponding to the initiation of cleavage microcracks in the material varied within the range 0.25-0.33 GPa. As the specimens are heated to 260°C, their cleavage strength increases from 0.31 to 0.50 GPa. Stevens and Pope [2] determined the cleavage strength of hot-pressed textured beryllium by the method of interferometric recording of the velocity of the free surface of specimens in the process of loading. For a typical duration of loading pulses of 0.4 μsec, the value of cleavage strength is equal to 0.6 GPa both for the intact and textured states of the material.

In [3], Bat'kov, Golubev, and others measured the cleavage strength of hot-pressed beryllium and the level of loading corresponding to the macroscopic cleavage fracture of specimens (this level was also measured at an elevated temperature of 400°C). The conditions of loading and the process of the cleavage fracture were recorded with a manganin pressure transducer. The conditions of macroscopic cleavage fracture were determined by the visual inspection of tested specimens. In the present work, we continue the research originated in [3] and perform the numerical analysis of the conditions of fracture of tested beryllium specimens by using two different approaches to this phenomenon.

We now briefly outline the experimental procedure used in [3] and present a sketch of the experimental data obtained in the indicated work. Disk-shaped specimens with a diameter of 90 mm and a thickness of 20 mm were loaded by an impact of an aluminum plate with a thickness of 4 mm accelerated to the required velocity by glancing detonation of a layer of gelatin explosives. To record the parameters of the tests, the specimens were placed between an aluminum screen with a thickness of 2 mm and a sublayer of Plexiglas with a thickness of 10 mm. The manganin pressure transducers were mounted on the boundaries of the specimens. The tests were carried out for three impact velocities: 129, 206, and 234 m/sec. In all these cases, the results of recording the behavior of pressure on the specimen-sublayer boundary confirmed the realization of the process of cleavage fracture. The first specimen preserved its macroscopic integrity but the other two specimens disintegrated into several longitudinal fragments. In the process of visual inspection of the lateral fracture surfaces of fragments, we discovered small cracks in the zones of probable cleavage. In experiments without recording the parameters of the tests, we realized direct loading of free specimens.

To determine the conditions of loading and fracture, we performed an elastoplastic numerical analysis of wave processes induced in beryllium specimens by impacts. For this purpose, we used a simple one-dimensional program based on the Lagrangian representation of basic equations solved by the method of finite differences. The characteristics of materials necessary for calculations are presented in Table 1, where \( \rho \) is density, \( c_0 \) and \( \lambda \) are...
<table>
<thead>
<tr>
<th>Material</th>
<th>( \rho, \text{g/cm}^3 )</th>
<th>( c_0, \text{km/sec} )</th>
<th>( \lambda )</th>
<th>( c_l, \text{km/sec} )</th>
<th>( c_t, \text{km/sec} )</th>
<th>( \sigma_e, \text{GPa} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>2.70</td>
<td>5.25</td>
<td>1.39</td>
<td>6.39</td>
<td>3.15</td>
<td>0.2</td>
</tr>
<tr>
<td>Beryllium</td>
<td>1.84</td>
<td>8.09</td>
<td>1.73</td>
<td>12.80</td>
<td>8.80</td>
<td>0.2</td>
</tr>
<tr>
<td>Plexiglas</td>
<td>1.18</td>
<td>2.59</td>
<td>1.51</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

the coefficients of the linear relationship \( D = c_0 + \lambda u \) between the mass and wave velocities, \( c_l \) and \( c_t \) are the longitudinal and transverse velocities of sound, respectively, and \( \sigma_e \) is the Hugoniot elastic limit. As a result of computations, it was established that, for impact velocities of 129, 206, and 234 m/sec, pulses with a typical duration of 1.5 \( \mu \)sec and amplitude values of longitudinal compressing stresses of 1.01, 1.59, and 1.8 GPa, respectively, are transferred from the aluminum screen to the specimen. If we do not take into account the fracture process, then, at the point with coordinate \( x = 13.6 \text{ mm} \) (measured from the screen-specimen boundary and corresponding to the location of cleavage), at time \( t = 3.5 \mu \text{sec} \) (measured from the impact), we observe the initiation of a tensile pulse with the same duration and the following amplitude values of tensile stresses: 0.43, 0.79, and 0.88 GPa. To take into account the fracture process in a simplified form, we select a special value of cleavage strength \( \sigma_c = 0.4 \text{ GPa} \). As soon as tensile stresses attain this level, the material is regarded as destroyed and the relevant boundary condition is specified for the corresponding coordinate. Time dependences of stresses on the specimen-sublayer boundary computed as indicated above are depicted in Fig. 1. The experimental data obtained by using manganin pressure transducers are also presented in Fig. 1. We observe satisfactory agreement between these data, which allows us to conclude that the selected value of cleavage strength is acceptable as well as the applied simplified approach to the process of cleavage fracture of extremely brittle materials such as beryllium.

The kinetic approach to the simulation of the processes of cleavage fracture of various materials was suggested by Seaman, Curran, and Shockey in [4]. The developed model of initiation and growth of damage developed in [4] was used, in particular, to describe the process of cleavage fracture of beryllium specimens under the conditions of their rapid heating by high-current electron beams. The general equations of this model describe the law of initiation of damage, namely,

\[
\dot{N} = \dot{N}_0 \exp \left( \frac{\sigma - \sigma_{n0}}{\sigma_i} \right)
\]

and the law of their ductile growth

\[
\dot{R} = \frac{\sigma - \sigma_{g0}}{4\eta} R,
\]

where \( \dot{N} \) is the rate of initiation of defects, \( R \) is the size of damage (for the case of brittle fracture, this is the radius of a microcrack), and \( \sigma \) is the actual level of stresses. The other quantities necessary for computations are parameters of the model of fracture. According to the data presented in [5], for hot-pressed beryllium, one can use the following values of these parameters: \( R_0 = 45 \mu \text{m} \), \( \dot{N} = 7 \cdot 10^{10} \text{cm}^{-3} \cdot \text{sec}^{-1} \), \( \sigma_{n0} = 0.27 \text{ GPa} \), \( \sigma_i = 0.021 \text{ GPa} \), \( \eta = 31.6 \text{ Pa} \cdot \text{sec} \), and \( \sigma_{g0} = 0.13 \text{ GPa} \).

The model of fracture described in [4] (with the parameters of hot-pressed beryllium taken from [5]) was studied by using the computer program applied in the present work to the elastoplastic analysis of wave processes. The results of computation of the behavior of stresses on the specimen-sublayer boundary carried out by using this kinetic model of fracture for impact velocities \( v_y \) of 129 and 234 m/sec are shown in Fig. 1. The experimental data and the results of numerical analysis performed under the assumption of instantaneous fracture are also presented in Fig. 1. Numerical computations performed by using the kinetic model of fracture also enable one to determine the space-time distributions of the degree of damage to the material in the zone of intense tension. In particular, in Fig. 2, for the indicated two impact velocities, we present the distribution of the degrees of damage \( \psi \) (equal to the ratio of the specific volume of damage to the mean specific volume of the material) along the \( x \)-axis at time \( t = 5 \mu \text{sec} \), when the intensity of tension becomes insignificant. As the time of computations increases to 6 \( \mu \text{sec} \), for an impact velocity of 234 m/sec, we observe an increase in the degree of damage to the material damage in the interval \( x = 13.5-13.6 \text{ mm} \). Finally, it becomes as high as 21\%.