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On projectile fragmentation at high-velocity perforation of a thin bumper

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HIGHLIGHTS

- High-velocity fragmentation.
- Smoothed particle hydrodynamics method.
- The statistical properties of the fragments cloud.
- Phase transition.

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ABSTRACT

By means of 3D numerical simulations, we study the statistical properties of the fragments cloud formed during high-velocity impact of a spherical projectile on a mesh bumper. We present a quantitative description of the projectile fragmentation, and study the nature of the transition from the damage to the fragmentation of the projectile when the impact velocity varies. A distinctive feature of the present work is that the calculations are carried out by smoothed particle hydrodynamics (SPH) method applied to the equations of mechanics of deformable solids (MDS). We describe the materials behavior by the Mie–Gruneisen equation of state and the Johnson–Cook model for the yield strength. The maximum principal stress spall model is used as the fracture model. It is shown that the simulation results of fragmentation based on the MDS equations by the SPH method are qualitatively consistent with the results obtained earlier on the basis of the molecular dynamics and discrete element models. It is found that the power-law distribution exponent does not depend on energy imparted to the projectile during the high-velocity impact. At the same time, our calculations show that the critical impact velocity, the power-law exponent and other critical exponents depend on the fracture criterion. Q2

1. Introduction

Dynamic fragmentation of solids due to impact or explosion has been investigated during a number of years [1–19]. Typical experimental observations of fragmentation correspond to heavy nuclei collision in atomic physics [3,4,10], collision of macroscopic bodies [1,7,8,11,19], collision of projectile with a massive barrier [1,5,16–18], the explosive fragmentation of shells [2,13], and the fragmentation of the projectile at a high velocity perforation of a thin bumper [6,9,12,14].

Experiments [6,9] on the high-velocity impact fragmentation for the projectile–bumper system showed (i) the threshold nature of fragmentation; (ii) the similarity of the debris cloud structure provided that the ratio of the bumper thickness to the projectile diameter is a constant. However, the current experimental resources cannot give a more detailed picture of the critical and scaling effects of the fragments distribution and investigate the fragments structure "in situ". This gap may be filled up by computer simulation.

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Possibility of critical behavior during the impact fragmentation was considered within the scope of some nuclei collision experiments on intermediate energy [3,4,10,20]. The difficulty here was that in finite systems observed in practice, the critical transition is not clearly identified; one can only speak about a fuzzy critical region but not about a sharp critical point. The methods, which determine whether the critical behavior exists in the finite system, are based on similarity between the considered fragment distribution and predictions of well-known theories of critical phenomena, such as liquid–gas transition [21] and percolation [22]. According to these theories for the infinite systems near a critical point the cluster size distribution possesses scaling properties and it may be reduced to a universal function. Moreover, the theories predict that when distance from the critical point $\varepsilon < 0$ one infinite cluster is present in the system, while no such cluster exists when $\varepsilon > 0$, where $\varepsilon = T - T_c$ for the liquid–gas transition (T—temperature), $\varepsilon = p_c - p$ in case of percolation (p—fraction of occupied nodes). In finite systems the same behavior is observed when the largest cluster is also counted separately; e.g., associating the heavy nuclear residue with the "infinite" cluster and the lighter fragments with the finite clusters one can see that these theories describe, at least qualitatively, the fragments size distributions [3,23,24]. These methods were afterwards applied to the study of the critical behavior of fragmentation in mechanical systems [11,13–18,25–27]. As a result of numerical simulation, it was found that with increasing energy of the system, the transition point from damage to fragmentation in the solid behaves like a critical point (second order phase transition [11]). It should be noted that in the papers on numerical modeling of fragmentation in the mechanical systems the fragmented object is represented either as a set of identical particles connected by a pair potential (by analogy with the method of molecular dynamics (MD)) [10,14,16,17], or as a set of elements of different shapes linked with each other via different types of weightless binding elements [11,13,18,24,26]. Dynamics of particles (elements), including both translational and rotational motion, is described in these models by the system of Newton equations. The most widely used approaches are 2-D and 3-D versions of discrete element method (DEM) [18,27].

Experiments [1,3–5,7,8,10,13,15,18,20,21,23,24,26–29] and numerical simulations [11,13,14,16,17,25,27–30] showed that the mass distribution of the fragments can be represented by a power function

$$n(m) \sim m^{-\tau} \qquad (1)$$

in some non-negligible range of fragments mass variation. Note that the relation (1) is a necessary but not sufficient condition for the critical behavior in fragmentation. At the critical point of percolation the exponent happens to be $\tau > 2.0$ in three dimensions [22]. Experiments on nuclear fragmentation yield values of τ consistent with this inequality [3,4,10], while experiments on fragmentation of brittle solids give values of τ both larger and smaller than 2.0 [11,13,15,17,25,29]. The minimum possible value of τ close to 1 was obtained in experiments on the fragmentation of liquid droplets [26].

These works reflected the following two main issues: the dependence of the exponent τ on the effective dimensionality of the fragmented object and dependence of τ on the energy transmitted to the object during impact or explosion. Experiments and numerical simulations have shown that there is a relationship between τ and effective dimension of the fragmented object, i.e. the exponent τ grows as the effective dimension increases. This behavior does not depend on the detailed dynamics of the fragmentation process, and can be explained by simple theoretical models [7]. Dependence of the exponent τ on the initial energy imparted to a fragmented object was obtained in experiments and numerical simulations [4,8,11,14,16,26,29,30]; it was found that the exponent τ increases with the initial energy. The authors [8,16,29] interpreted this behavior as an example that the fragmentation is not a self-organizing phenomenon, in contrast to the assumption made in Ref. [5]. Generally speaking, it casts doubt on the critical nature of fragmentation, which was discussed in Refs. [11,13,18,25–27]. In experiments on collisions of heavy nuclei [31,32] and in experiments on the fragmentation of liquid droplets [26] it was found that the dependence of the exponent of power distribution τ on the impact velocity V is non-monotonic and has a minimum. Such a minimum for τ was interpreted by the authors of these works as an indication of the fragmentation phase transition. Independence of the exponent τ on imported energy has been found in the studies [5,13,18,27,30]. At the same time the dependence of τ on the state of the system prior to its fragmentation [30] or on constitutive equation of the material was shown [5,7,18,25]. Moreover, it was stated in Ref. [27] that the apparent dependence of τ on the imported energy found in a number of works was related to misinterpretation of the results of measurements or numerical calculations.

In contrast to the above works, in this paper the numerical simulation of fragmentation was carried out on the basis of the complete system of equations of mechanics of deformable solids (MDS) in three-dimensional formulation by the smoothed particle hydrodynamics (SPH) method [33–36]. The maximum principal stress spall model was used as the fracture model in the numerical simulations.

In the present work we consider the problem of the fragmentation of aluminum projectile on a thin mesh bumper at high-velocity impact. Selecting the mesh as a bumper allows one to significantly reduce the mass of the fragments formed in the bumper fragmentation, i.e. to reduce the influence of secondary interactions on the movement of the projectile fragments.

Simulation of fragmentation based on the MDS equations at least allows us to check the conclusions drawn on the basis of the MD and DEM models, and to identify the relation of the fracture criterion and the results obtained.

2. Numerical simulation method and material model

2.1. SPH method

Three-dimensional (3D) numerical modeling was performed on the basis of the complete system of MDS equations by the SPH method with the aid of the LS-DYNA code of version 971 including SPH calculation module [37]. The SPH method