Simulation of ceramics fracture due to high rate dynamic impact

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Abstract. In this paper dynamic fracture process due to high-speed impact of steel plunger into ceramic sample is simulated. The developed numerical model is based on finite element method and a concept of incubation time criterion, which is proven applicable in order to predict brittle fracture under high-rate deformation. Simulations were performed for $ZrO_2(Y_2O_3)$ ceramic plates. To characterize fracture process quantitatively fracture surface area parameter is introduced and controlled. This parameter gives the area of new surface created during dynamic fracture of a sample and is essentially connected to energetic peculiarities of fracture process. Multiple simulations with various parameters made it possible to explore dependencies of fracture area on plunger velocity and material properties. Energy required to create unit of fracture area at fracture initiation (dynamic analogue of Griffith surface energy) was evaluated and was found to be an order of magnitude higher as comparing to its static value.

1. Introduction

The investigation of fracture properties of ceramics is of big interest due to application of these materials in protection systems. Multi-layered ceramic composites are used in bulletproof vests and demining devices due to their exceptional properties (good impact energy absorption, low weight). In order to optimize construction and design of protection systems elaborate numerical schemes for simulation of impact into ceramic targets should be developed. Such numerical models should take into account peculiar properties of dynamic fracture [1]. Despite considerable advances in theoretical studies of impact problems, generally applicable fracture criterions for ceramic materials have not been developed yet [2].

In the presented paper the numerical scheme involves incubation time fracture criterion which is proven to be an effective tool for fracture process simulation for a wide range of brittle and quasi-brittle materials subjected to dynamic loading [3, 4]. The developed scheme is based on finite element method and is used to simulate impact of steel cylindrical plunger into round ceramic plate. Due to obvious axial symmetry of the problem two-dimensional formulation is used. Both bodies (target and plunger) are supposed to show purely elastic behaviour up to the moment of fracture. Temperature effects are neglected in the presented research. Such simplifications of the model made it possible to concentrate on fundamental features of dynamic fracture process—evolution of fracture surface in the target, fragmentation and surface energy (analogous to Griffith's surface energy) calculation.

Table 1. Target material properties.

Density ρ, kg/m^3	6000
Young's modulus E, GPa	200
Poisson's ratio ν	0.25
Critical stress intensity factor K_{IC}, MPa $\sqrt{\text{m}}$	13.3
Ultimate tensile stress σ_c, MPa	750

Table 2. Plunger material properties.

Density ρ, kg/m^3	7860
Young's modulus E, GPa	200
Poisson's ratio ν	0.25

2. Problem formulation

Plunger and target are supposed to be linear elastic bodies and their stress-strain state is defined by Lame equations and Hook's law:

$$\rho\frac{\partial^2 \bar{U}_i}{\partial t^2} = (\lambda + \mu)\, \nabla_i \left(\nabla \cdot \bar{U}\right) + \mu\Delta U_i, \tag{1}$$

$$\sigma_{i,j} = \delta_{i,j}\lambda\nabla \cdot \bar{U} + \mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right). \tag{2}$$

The ceramic plate is supposed to be fixed on its outer radius. The plunger initial velocity V is in the direction normal to the plate surface.

Material properties for the target are typical for $ZrO_2(Y_2O_3)$ ceramics [5,6]. The plunger is supposed to have properties of steel. Tables 1 and 2 give the material properties utilized for the simulation.

3. Fracture criterion and simulation technique

To perform correct simulation of fracture in ceramics due to impact of a plunger one should choose an adequate fracture criterion, which will be able to predict fracture in transient loading conditions. While classical fracture criteria (like critical stress criteria or criteria based on dynamic fracture toughness concept) tend to be inapplicable for dynamic loading cases [7], incubation time fracture criterion may be regarded as a universal tool for dynamic fracture prediction [8,9]. It is supposed that a similar approach can be used to predict fracture initiation, evolution and arrest in ceramic materials [10] for the studied class of problems. The criterion for fracture event at point x, at time t, is formulated in the following way [11]:

$$\frac{1}{\tau}\int_{t-\tau}^{t}\frac{1}{d}\int_{x-d}^{x}\sigma(x',t')dx'dt' \geq \sigma_c, \tag{3}$$

where τ is the microstructural time of a fracture process (or fracture incubation time)—a parameter characterizing the response of the material to applied dynamical loads (i.e. τ is constant for a given material and does not depend on problem geometry, the way a load is
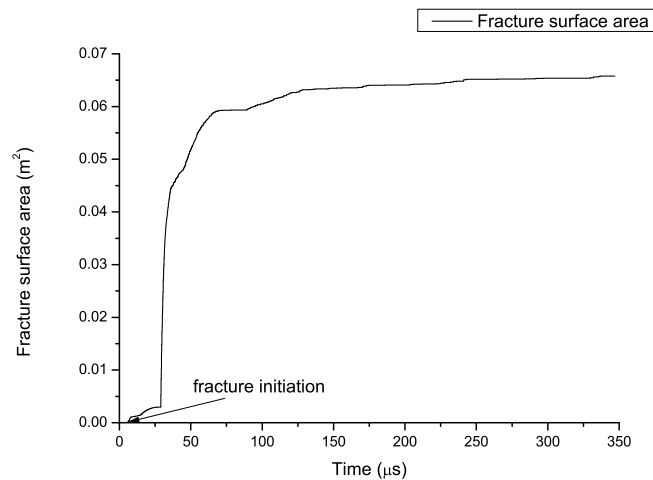
Figure 1. Fracture surface area as a function of time.

applied, the shape of a load pulse or its amplitude). d is the characteristic size of a fracture process zone and is constant for the given material and chosen scale. d is calculated in the following way $d = \frac{2}{\pi} \frac{K_{IC}^2}{\sigma_c^2}$ [1]. $\sigma(x,t)$ is stress at a point x, changing with time, and σ_c is its critical value (ultimate stress or critical tensile stress found in quasi-static experiments).

Fracture criterion (3) is integrated into numerical scheme, which is based on finite element method. ANSYS software package is used as a solver and fracture criterion is implemented via ANSYS user programmable feature (UPF) in FORTRAN. In addition to this external program in C++ is used to control and optimize solution progress and manage output data. Element size in the mesh is chosen to be equal d and thus minimal length of a microcrack in the sample will be also equal d which is in agreement with approach based on (3). Time step of the solution is chosen to be smaller than time needed the fastest wave to pass through single element of the mesh.

In the constructed mesh, each element has its own set of nodes—neighbor elements do not have common nodes, however nodes with equal coordinates have coupled degrees of freedom. This means that while condition (3) is false they behave as a single node, and as soon as (3) is true the nodes are separated and new surface appears.

4. Results
Experiments for incubation time evaluation in ceramics have not been performed yet and value of τ for $ZrO_2(Y_2O_3)$ ceramic is unknown. However this makes it possible to investigate influence of incubation time alternation on fracture process features. Reasonable range for possible incubation time variation was chosen keeping in mind values typical for other brittle materials [9].

4.1. Fracture surface evolution
At each step of the solution fracture, surface area is calculated in the external program. While fracture surface area is calculated axial symmetry of the problem is considered: length of each microcrack is multiplied by the distance to symmetry axis and then added to the total fracture surface area. When fracture surface area stops to increase the solution is stopped. Typical graph of fracture surface area—time dependence is presented in figure 1.

It should be noticed here, that parts of the ceramic target separated in course of the fracture process do not interact with each other, which is, of course, a significant simplification of the model. This simplification can have a kind of physical reasoning, connected to removal of energy from the system (as separated parts are no longer interacting with the fracturing media), that in real experiment is consumed by fracture, including heating, surface energy, acoustic emissions, material dumping, etc. Possibly, interaction of separated particles with other particles, plunger and the resting bulk of ceramic material should not be neglected, but this is the topic for a future study.

As plunger initial velocity is altered the amount of energy spent for fracture changes. Thus the induced damage also changes. Figure 2 depicts dependence of final fracture surface area on plunger initial velocity. These calculations were performed for 1 μs incubation time value. Variation of incubation time value provided dependence of final fracture surface area on τ (see figure 3). As seen from the graph higher incubation time values correspond to bigger final fracture surface area. This may be referred to the fact that greater incubation time values induce fracture closer to the sample edges. The data was obtained for 100 m/s velocity of the plunger. Variation of the incubation time used in fracture criterion (3) in fact means the variation of the material as the incubation time is a material property responsible for material response to dynamic loading.

4.2. Fragmentation
In this study, the mesh of the target is interpreted as a graph with elements being nodes of this graph. If two elements are separated by a microcrack two nodes of the graph have no edge between them. Such an approach makes it possible to apply well developed algorithms of graph theory to investigate the distribution of fragments (being connected components from the graph theory point of view). Variation of the incubation time value provided an opportunity to investigate dependence of number of separate fragments appearing because of fracture on incubation time. This dependence is presented in figure 4. As incubation time increases number of fragments drops. In addition to this distribution of sizes of fragments was studied (figure 5). One should note here that several points were eliminated from the graph to highlight zone of interest (middle-sized fragments).

4.3. Surface energy. Dynamic analogue of Griffith's constant
The classical approach to fracture mechanics going back to Griffith [12] is based on the statement that a crack propagates if this process leads to a decrease in the total energy Π of the system. For a plate of unit thickness, the crack-growth conditions can be written as

$$-\frac{\partial \Pi}{\partial L} = 2\gamma. \tag{4}$$

Griffith initially interpreted the quantity 2γ as the surface energy, because it represented the specific work (per unit area) expended to form a new surface. Irwin and Orowan showed that this quantity should be interpreted as the total work (including the plastic one) in the fracture zone. This work can be taken as the resistance to a certain dissipative process proceeding in a small region near the crack tip. The study of this characteristic includes the determination of its physical origin (different for different classes of materials) and its measurement.

For the case of linearly elastic body the Griffith's constant is equal to

$$\gamma = \frac{K_{Ic}^2}{2E}, \tag{5}$$

where E is Young's modulus and K_{Ic} is critical stress intensity factor for mode I loading. Thus, γ can be indirectly determined in this case from the standard tests. However it was shown [13]
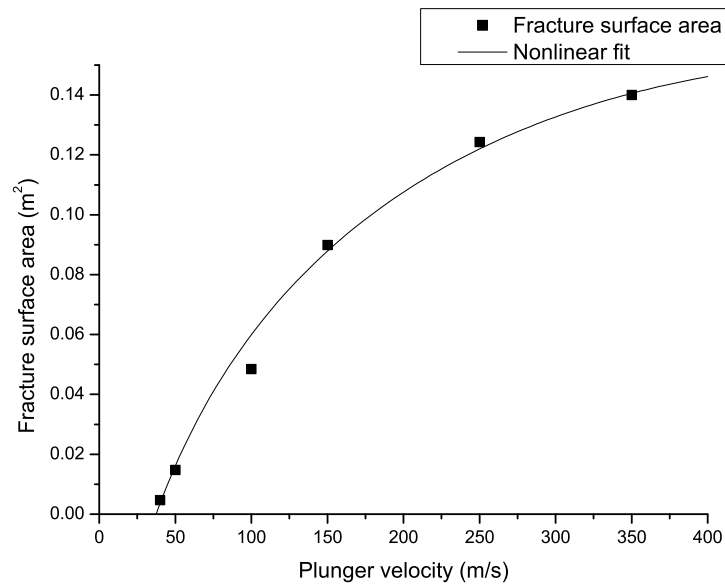
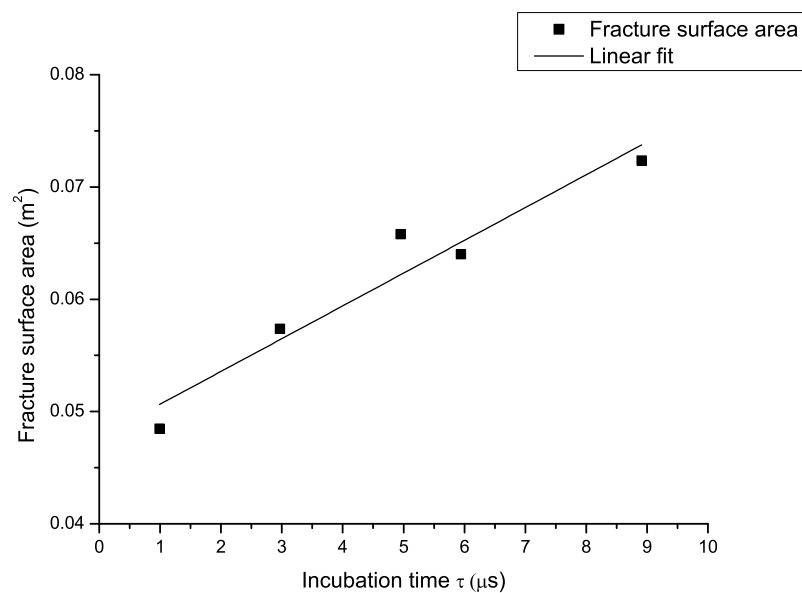**Figure 2.** Fracture surface area—plunger initial velocity dependence.

Figure 3. Final fracture surface area as a function of the fracture incubation time.

that in case of dynamic loading surface energy appears to be much higher than values obtained for static cases.

Here the difference between the initial (E) and the residual (E_r) kinetic energies of the plunger is supposed to be equal to the change of the potential energy of the target. According to the Griffith's approach, variation of the potential energy is the energy spent for new surface
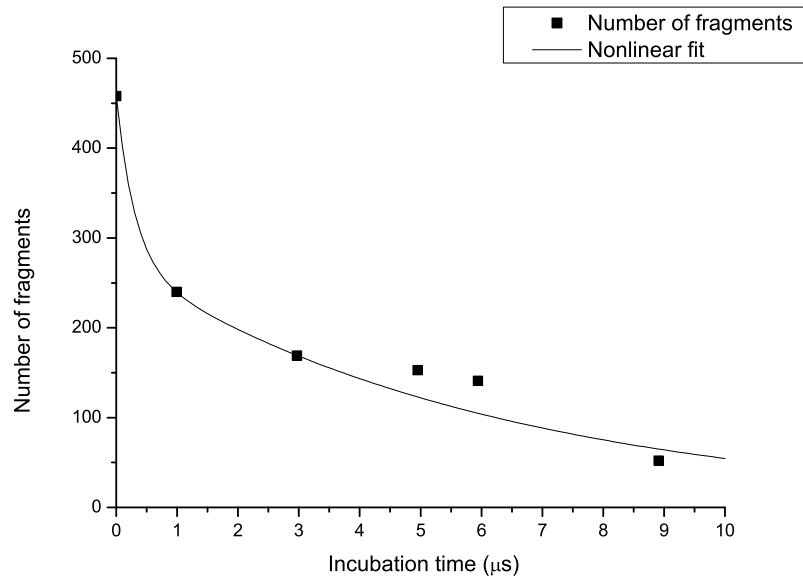
Figure 4. Number of fragments in the end of fracture as function of incubation time.
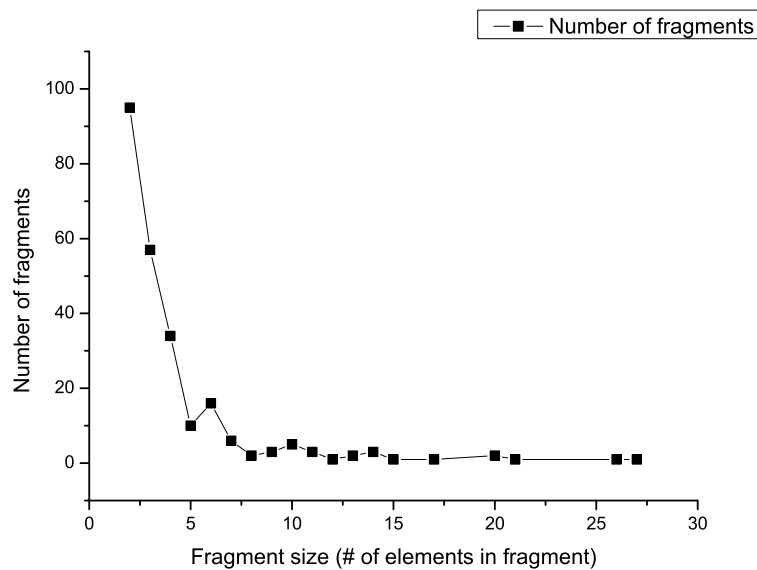

Figure 5. Number of fragments of each size for the plunger velocity 250 m/s and 1 μs incubation time value.

creation—Π. Thus, it is possible to calculate Π as the difference between $E = mV^2/2$ and $E_r = mV_r^2/2$ where m is the plunger mass and V and V_r are the initial and the residual velocities of the plunger. One should note here that the potential energy of the system (target in our case) also includes the energy of the waves and the kinetic energies of moving fragments.

To calculate the dynamic analogue of the Griffith's energy—γ_d—the following formula can be utilized:

$$\gamma_d = \frac{d\Pi}{dS}\bigg|_{S=0}, \qquad (6)$$

where S is the area of fracture surface created in a result of interaction. Calculation of γ_d using (6) gives $\gamma_d = 1171\frac{J}{m^2}$ for the studied case. This value is considerably higher (approximately an order of magnitude) than fracture surface energy evaluated in quasi-static loading conditions [14].

5. Conclusions

The presented research is the first attempt to analyze and simulate dynamic fracture of ceramics due to impact of steel plunger applying incubation time approach. Dependencies of final fracture surface area and fragmentation properties on incubation time (and thus material) were investigated. Moreover, fracture surface area for dynamic fracture was calculated appearing to be an order of magnitude higher than the value for static loading conditions.

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