

Numerical simulation of ceramic plate penetration by cylindrical plunger

Nikita Kazarinov, Vladimir Bratov, Yuri Petrov, Lucjan Witek,
Arkadiusz Bednarz
nkazarinov@gmail.com

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 to be applicable in order to predict brittle fracture under high-rate deformation. Simulations were performed for ZrO₂(Y₂O₃) 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 criteria 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 behavior 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 Griffiths surface energy) calculation.

2 Problem formulation

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

$$\rho \frac{\partial^2 \mathbf{u}_i}{\partial t^2} = (\lambda + \mu) \nabla_i (\nabla \cdot \bar{\mathbf{u}}) + \mu \Delta \mathbf{u}_i, \quad (1)$$

$$\sigma_{i,j} = \delta_{i,j} \lambda \nabla \cdot \bar{\mathbf{u}} + \mu \left(\frac{\partial \mathbf{u}_i}{\partial x_j} + \frac{\partial \mathbf{u}_j}{\partial x_i} \right). \quad (2)$$

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

Material properties for the target are typical for ZrO₂(Y₂O₃) ceramics [5, 6]. The plunger is supposed to have properties of steel. Tables 1 and 2 give the material properties utilized for the simulation.

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

Table 1: Target material properties

Density, $\rho, \frac{\text{kg}}{\text{m}^3}$	7860
Young's modulus, E, MPa	200
Poisson's ratio, $\nu,$	0.25

Table 2: Plunger material properties

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]:

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

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 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 for 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.

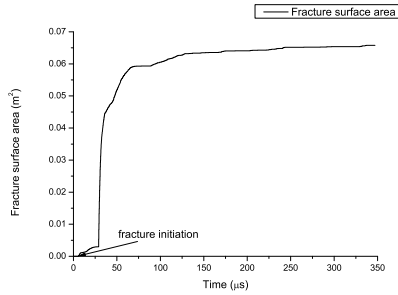


Figure 1: Fracture surface area as a function of time.

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 $1 \mu\text{s}$ 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 100m/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.

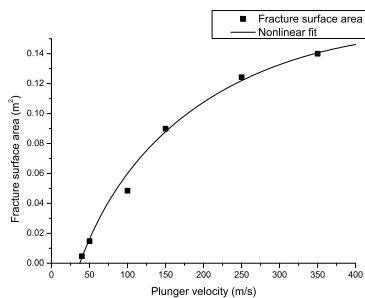


Figure 2: Fracture surface area - plunger initial velocity dependence.

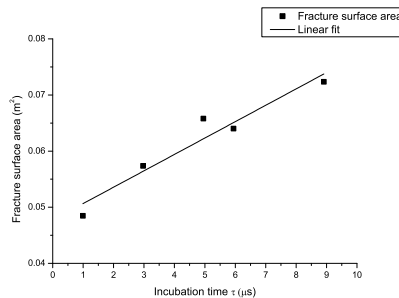


Figure 3: Final fracture surface area as a function of the fracture incubation time.

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 approach allows application of well developed algorithms from graph theory to investigate fragments of the target (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 as a result 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).

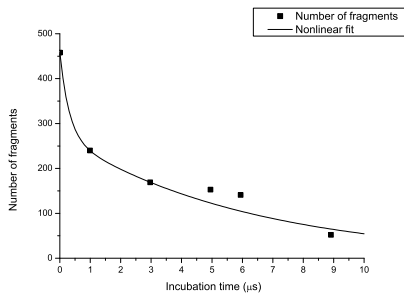


Figure 4: Number of fragments in the end of fracture as function of incubation time.

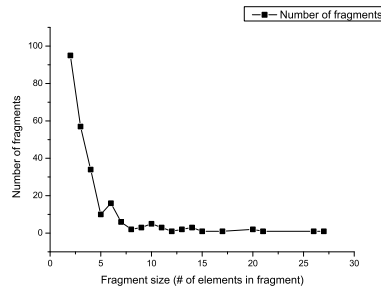


Figure 5: Number of fragments of each size for the plunger velocity 250 m/s and 1 μs incubation time value.

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

$$-\frac{\partial \Pi}{\partial L} = 2\gamma. \quad (4)$$

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

$$\gamma = \frac{K_{Ic}^2}{2E}, \quad (5)$$

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

In the present study the energy spent for fracture Π is calculated as difference between initial (E) and residual (E_r) kinetic energies of the plunger. These energies are calculated using formulas $E = mV^2/2$ and $E_r = mV_r^2/2$ where m is the plunger mass and V and V_r are initial and residual velocities of the plunger. To calculate dynamic analogue of Griffith's energy - γ_d - one should apply the following formula:

$$\gamma_d = \left. \frac{d\Pi}{dS} \right|_{S=0}, \quad (6)$$

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.

6 Acknowledgments

The authors acknowledge Saint Petersburg State University for a research grant 6.39.319.2014. The research and publication preparation was also supported by RFBR research grants 14-01-00814 and 13-01-00598, the President Grant for Government Support of Young Russian Scientists MK-7596.2015.1 and the academic programs of the Russian Academy of Science and FP7 EU MARIE CURIE Project TAMER No. 610547

7 References

References

- [1] Petrov Y V 1991 On "Quantum" Nature of Dynamic Fracture of Brittle Solids. *Dokl. Akad. Nauk USSR* **321**,66-8

- [2] Ravi-Chandar K 2004 *Dynamic Fracture* (Elsevier) 264
- [3] Bratov V 2011 Incubation time fracture criterion for FEM simulations *Acta Mechanica Sinica* **27(4)** 541-49
- [4] Bratov V, Petrov Y 2007 Application of incubation time approach to simulate dynamic crack propagation *An International Journal of Fracture* **146** 53-60
- [5] Masaki T 1986 Mechanical Properties of Toughened ZrO₂-Y₂O₃ Ceramics *Journal of American Mechanical Society* **69(8)** 638-40
- [6] Winnbust A J A, Keiser K, Burggraaf A J 1983 Mechanical Properties and Fracture Behaviour of ZrO₂-Y₂O₃ Ceramics *Journal of Materials Science* **18** 1958-66
- [7] Bratov V A, Morozov N F, Petrov Yu V 2009 *Dynamic Strength of Continuum* (St. Petersburg University Press, Saint Petersburg) 224
- [8] Kazarinov N, Bratov V, Petrov Y 2014 Simulation of Dynamic Crack Propagation under Quasi-Static Loading *Doklady Physics* **59(2)** 99-102
- [9] Smirnov V, Petrov Yu V, Bratov V 2014 Energy of a solid sphere under non-stationary oscillations *Science China Physics, Mechanics and Astronomy* **55(1)** 78-85
- [10] Petrov Y V, Taraban V V 1999 On Process Zone Size Criteria of Fracture In Brittle Solids *Physico-Chemical Mechanics of Materials* **1** 77-82
- [11] Morozov N, Petrov Y 2000 *Dynamics of fracture* (Springer-Verlag, Berlin.)
- [12] Griffith A 1921 Phenomena of Rupture and Flow in Solids *Philosophical transactions of the Royal Society of London* **A221** 163-98
- [13] Bratov V A, Gruzdkov A A, Krivosheev S I, Petrov Yu V 2004 Energy balance in the crack growth initiation under pulsed-load conditions *Doklady Physics* **49(5)** 338-41
- [14] Lawn B 1993 *Fracture of Brittle Solids Second Edition* (Press Syndicate of the University of Cambridge, Melbourne) 378

Nikita Kazarinov, Saint Petersburg State University, Universitetskaya Emb. 7-9, 199034, Russia

Vladimir Bratov, Saint Petersburg State University, Universitetskaya Emb. 7-9, 199034, Russia

Yuri Petrov, Saint Petersburg State University, Universitetskaya Emb. 7-9, 199034, Russia

Lucjan Witek, Rzeszow University of Technology, al. Powstacw Warszawy 12, 35-959 Rzeszow, Poland

Arkadiusz Bednarz, Rzeszow University of Technology, al. Powstacw Warszawy 12, 35-959 Rzeszow, Poland