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Study of ceramic tube fragmentation under shock wave loading

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Abstract

In this paper we investigate the fragmentation of tubular alumina samples under shock-wave loading. Test of tubular samples was performed on a universal experimental set up of electric explosion conductor Bannikova et al. (2013a). The blast tube destroyed into fragments having as rectangular or irregular geometric shapes. The mass distribution obtained by “method of photography” and “method weighting” are in good agreement Bannikova et al. (2013b). For tubes with wall thickness $d = 2.05$ mm formed fragments described of by double distribution: small fragments whose size is much smaller than the thickness of the tube - distribution power law, large fragments described as exponential and logarithmic distribution are equally. The inflection point of the distribution curves moves toward smaller scales with increasing energy density. Besides other determined that Weibull function a good description of the distribution of all the fragments by mass.

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Keywords: Fragmentation distribution; electroexplosion; shock wave; alumina ceramic; form factor.

1. Introduction

Still during the Second World War by Professor of Physics N. F. Mott were undertaken the first attempts to describe the statistics of fragmentation objects (cylindrical projectiles) subjected to intensive pulsed load. Grady (2006). Since then, the study of the problems of fragmentation continues by our time, therefore significant experimental and theoretical data accumulated. In the world objects are investigated the dimensions of it varies from laboratory specimens crumbling into fragments of weighing less than a gram to the arctic ice fields photographed by satellite or galaxies crumbling meteorites and asteroids. Studied objects of different shapes – spheres, cubes, plates, rings, rods, and of the most diverse materials – copper, lead, glass, concrete, ceramics, rocks, ice, clay, gypsum, soap, wax, potatoes. The objects are investigated under different loading conditions (impact, creep, bending and compression).

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The main tool of the fragmentation statistical regularities research is determination the fragments distribution by size or masses, in other words, the definition number of fragments $N(r, m)$ with size r or mass m greater than some predetermined. The distribution form depends on many factors: the magnitude of energy expended for the destruction of the sample, the material properties – brittle or ductile, elastic or plastic; dimensionality – 2D for example, plate, rod and 3D – ellipsoid. Depending on the conditions observed distributions of the following types: log-normal, power law (D. L. Turcotte), the distribution of Mott, exponential (D. E. Grady), the Weibull distribution and combination of exponential and power distributions (J. J. Gilvarry).

In this paper we investigate the fragmentation of 2D objects - tubular ceramic samples (alumina), in conditions of the shock-wave loading.

Nomenclature

m_s	mass of sample
d	wall thickness of tube
h	height of tube
r_1	outer radius of tube
r_2	inner radius of tube
ρ_o	density ceramics
W_C	energy stored in the capacitor battery
Q_W	energy expended on evaporation conductor at room temperature
w	density energy of the explosion
N	quantity of the fragments of a given mass
m_f, m	mass of the fragment
d^*	character size of the fragment
S	size of the image area the fragment on photo
S_{in}	the inner surface of the tube, of the fragment
S_{out}	the outer surface of the tube, of the fragment
m^*	mass of fragment by method photography
α	form factor

2. Experiment and materials

Loading of tubular specimens was carried out on a universal experimental setup of electric explosion conductor Bannikova et al. (2013a). Schematic diagram and appearance of the experimental setup are presented in Bannikova et al. (2013a); Bannikova et al. (2013b). It is a complex that includes cylindrical explosion chamber diameter of 0.24 m and a height of 0.085 m, a high voltage source (HVS, U_{max} = 5÷15 kV), storage capacitors system (C_o = 0.022 ÷ 0.44 mF), discharger and discharge ignition system (manual) on the conductor (copper wire diameter d_w = 0.1 mm). Damping material is set on the inner side surface and on the bottom of the cuvette in order to not destroy the wall of the chamber by shock wave. Tubular sample with an axial conductor were placed in the explosion chamber filled with distilled water. The shock wave was initiated in the liquid as a result electric explosion conductor by discharge of the capacitor bank charged from HVS. Water decreased "energy" flying fragments that excluded their further fragmentation by collision fragments with each other and the walls of the chamber. During the tests we performed a series of experiments at different energy of the capacitor bank. Amperage is measured on the conductor with Rogowski coil. The current density was about 10^{11}÷10^{12} A m^{-2}.

Alumina tubes had outer and inner radius r_1 = 5.9 mm, r_2 = 3.9 mm (the thickness of the tube wall d = 2.05 mm) and a height h was in the range 12.7÷16.7 mm (Fig. 1, (a, b)). The density of the tube material was $\rho_o \approx$ 2.6 kg m^{-3}. A result conductor explosion the tube fragmented as show in Fig. 1 (c), they had rectangular and irregular geometric forms Bannikova et al. (2013b).

Optical microscopy showed that the fragments have a developed cracks structure (Fig. 2). Main cracks are vertical gap cracks formed in result a radial loading of explosive wave, and horizontal cracks are on middle of the sample are crack of reset. Appearance of the last cracks possibly due to that maximum of the velocity profile of the explosive waves necessary on the middle of tube.

To collect fragments from liquid used polyethylene film. It was placed on the bottom chamber, under tube. After drying of fragments at room temperature (20°C), they were weighed on an electronic balance HR-202i. Mass of fragments was on average ~ 98% for all test samples. It was decided to consider two methods for determining the mass of fragments, because the part of fragments by mass does not exceed the resolving power of the electronic balance, 0.0001 g.

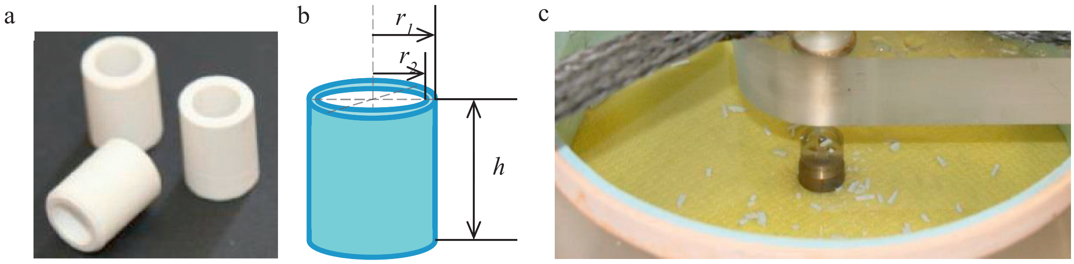

Fig. 1. (a) an external view of the tube; (b) a scheme of the sample; (c) the distribution of fragments in the water after the explosion of the tube.

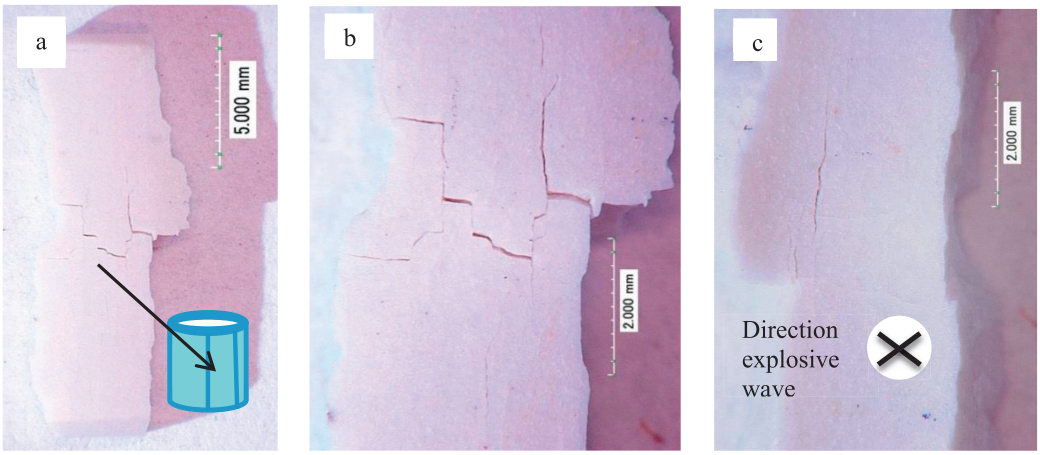

Fig. 2. Cracks on the surface of the fragment, the energy density of the explosion w = 5.9 J g^{-1}: (a) appearance fragment; (b) outer side fragment; (c) the inner surface of the fragment.

2.1. The Method of weighing

Fragments were sieved through a laboratory sieves system and were weighed on an electronic balance HR-202i. Distribution of the quantity fragments N in dependence from weight m_f exceeding some defined in logarithmic coordinates for all the tested samples is shown in Fig. 3. Since part of the energy stored within the capacitor battery was spent on the processes occurring with the conductor: heating to the melting temperature of the conductor, melting the conductor, heating to the evaporation temperature of the material and evaporation of the conductor, that is some energy Qw, and the mass of the samples m_s was different, it was decided to use the term "the density of energy", w. The density of energy was estimated by Eq. (1):

$$w = \frac{W_C - Q_W}{m_S} \quad (1)$$

With right from No. of sample shown the corresponding value of the specific energy w (Fig. 3). In Fig. 3 we can distinguish two areas corresponding to the different distribution laws. Since our work loaded ceramic tubes are two-dimensional objects and their fragments have two distributions. For large fragments, whose thickness is commensurate with the thickness of the sample (with the thickness of the tube wall) – one distribution law, for small (volume fragments) – another distribution law. These results agree well with Katsuragi et al. (2005). It has been established that the inflection point of distribution law $N(m_f)$ is shifted toward smaller scale with increasing energy density.

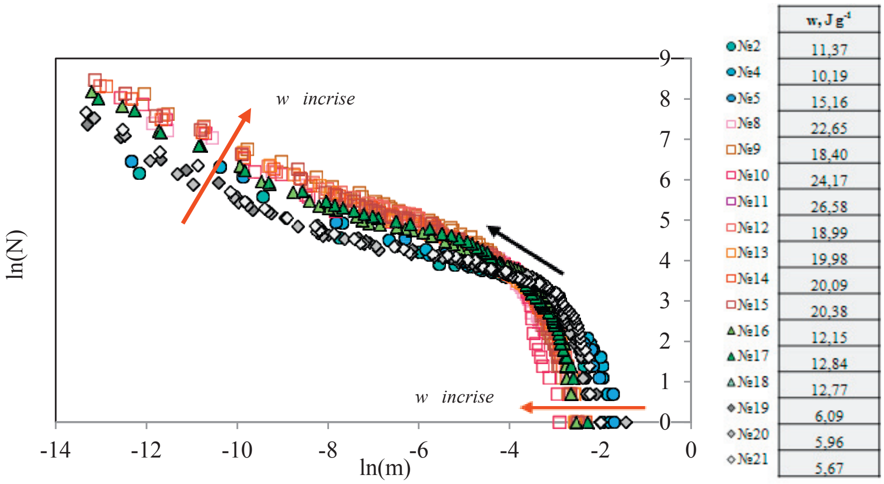

Fig. 3. The distribution of fragments by weight, logarithmic coordinates.

Experimental data processing showed that the distribution of fragments $N(m_f)$ weight less than the average weight of $m_f \le m_{mean}$ and with the size of the fragment much less than the character size of the tube $d^* < d$, is described power laws, here $B' = e^B$, Eq. (2).

$$N = B' \cdot m^A, \quad (2)$$

where the coefficient "B" increases with an increase of energy density w, as shown in Fig. 4 (a, up), and the coefficient A = -0.47 ± 0.02 - the exponent of m is constant independently of entered energy density w tubes destruction and this can be seen in Fig. 4 (a, below).

During processing of large fragments ($m_f > m_{mean}$, $d^* = d$) is obtained that this fragments distribution described well as an exponential law and the logarithmic law (square deviation R^2 = 0.96÷0.98). Eq. (3). Change of coefficients in these distributions depending on the specific energy is shown in Fig. 4, (b, c). The higher energy of the explosion the smaller fragments with a large mass, so the inflection point of the distributions moves toward smaller scales (Fig. 3, black arrow).

$$N = B \cdot e^{Am}, \quad N = A \cdot \ln(m) + B \quad (3)$$

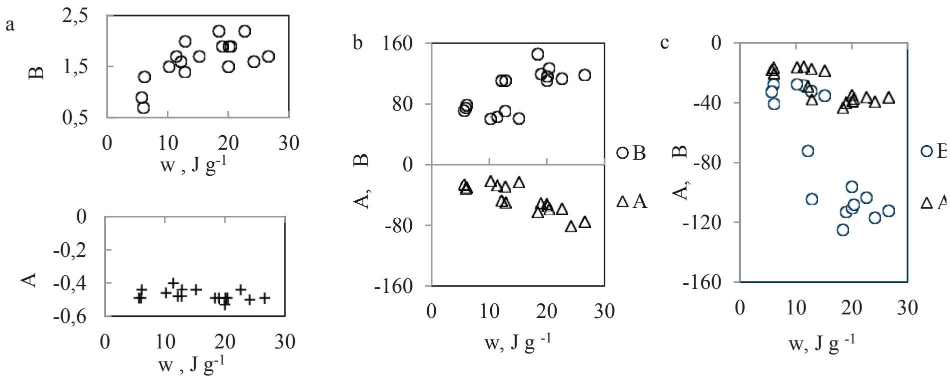

Fig. 4. (a) change of the coefficients B and A in the distribution power law for small fragments depending on the specific energy; the coefficients A and B: (a) in the exponential distribution; (c) in the logarithmic distribution, Eq. (3).

2.2. The Method of photography

In addition to weighing the distribution of fragments by size estimated by digital photography, since the accuracy of 0.0001 g weights not possible to measure the mass of the majority of small fragments. Camera CANON 7D 16.1 Mpix was used to photographing fragments (Fig. 5, (a)). Fragments were placed by hand on black backing. In the right side of image are located those fragments which were individually weighed on an electronic balance, and fragments with height corresponded to tube thickness $d^* = d$ (Fig. 5). Fragment image area was calculated using the software package to process digital photographs (Fig. 5, (b)). Mass of large fragments ($d^* = d$) were calculated by formula Eq. (4), where S – the average area of the image area of fragment obtained by processing two photographs, $S = (S_{out}+S_{in})/2$. Mass small fragments (3D, $d^* < d$) could not be calculated by the method described in Brodskii et al. (2011), since the coefficient “factor of form” α characterizing the geometry of the fragment, was different for tube fragments. “Form factor” for smaller fragments was calculated by the method described below.

$$m^* = S \cdot d \cdot \rho \tag{4}$$

Mass of large fragments was subtracted from the mass of all fragments of the sample and mass of all small fragments were found, $m_{d^*<d}$. Number of small fragments was using digital image processing. Then, the average weight and the average area of small fragments in degree 3/2 were calculated. And the “form factor” was calculated, Eq. (5). The data analysis showed that “form factor” α is the same for fragments with $d^* < d$ for all ceramic tubes: 0.14 ± 0.04. Substituting these values in the Eq. (6) were calculated the weight of each small fragment. This method we have called the “method of photography”.

$$\alpha = \frac{< m_{d^*<d} >}{\rho \cdot < S^{3/2}_{d^*<d} >} \tag{5}$$

$$m^* = \alpha \cdot S^{3/2} \cdot \rho \tag{6}$$

The results of distributions $N(m)$ and $N(m^*)$ obtained by two methods are in good agreement. In the power-law of the fragments distribution with sizes d*<d deviation in the mass (m, m^*) was ~ 8 percent. For fragments with sizes $d^*=d$ deviation in exponential laws of fragments distribution by weight, $N(m)$ and $N(m^*)$, assessed as 13% and in logarithmic laws distribution deviation was 15% (Eq. (3))

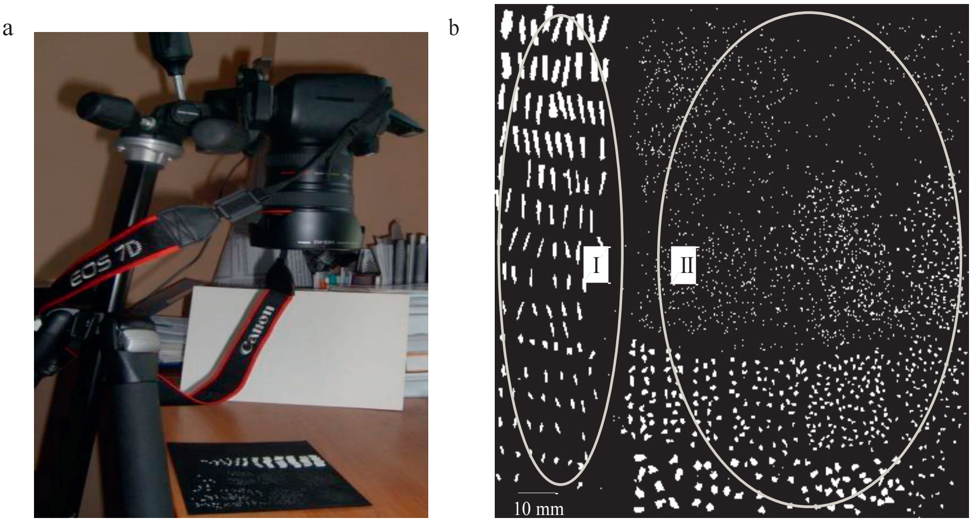

Fig. 6. (a) camera CANON 7D, 16.1 Mpix; (b) processed photo of fragments, 10 mm = 240 pix: I - rectangular shape, d*=d, II - irregular geometric form, d*<d.

3. Conclution

Established that fragmentation of ceramic tubes described by double distribution: for fragments with $d^* < d$ - a power law distribution; for fragments with $d^* = d$ rightly both exponential and logarithmic distribution. It has been shown that the inflection point in the distributions $N(m)$ shifts toward smaller scales with increasing energy density of tubes explosion. Ceramic tubes have a characteristic parameter L, less than unit, which calculated as the ratio of d to the inner tube radius r_2. Tentative experiments loading of tubes with $L > 1$ gives one exponential distribution, as in the case of shells from the walled cylinders in the works of Grady (2006).

Found that the distributions obtained on the “weighting method” and “method of photography” are in good agreement, and subsequently use of them to speed up data processing.

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