Deformation and fracture of metal ring samples under the explosion of conductors

Morozov V.A., Lukin A.A., Atroshenko S.A., Gribanov D.A., Petrov Yu.V.

Abstract

The technique of deformation and fracture of ring metal samples was developed using the explosion of conductors in elastomers of cylindrical shape. The work on the optimal choice of the elastomer was carried out. Methods for measuring the displacement of the sample surfaces and the radial pressures were suggested. On the base of these methods the characteristics of the stress-strain state of the matter were investigated. A structural analysis of fracture surfaces was carried out.

Keywords: fracture; ring samples; electric explosion of conductors; structural analysis.

1. Introduction

To date, a lot of methods for high-strain-rate, deformation and fracture of structural materials are developed. Among them it is possible to distinguish electro-physical methods, used lately, based on electromagnetic action (Zhang and Chandar, 2006, Morozov et al., 2011, Morzov et al., 2014), or electrical explosion of conductors (Imbert et al., 2015). The mechanisms that lead to the improvement of the quality of processing of materials under high strain rates, is not fully understood, which significantly limits the possibility of modeling these processes. For a better understanding of the mechanisms of high-speed deformation of materials and the development of accurate models it is necessary to carry out experimental studies to obtain reliable data on the stress-strain state of materials at...
high strain rates. The subject of this work is to develop a method of loading and deformation of the ring samples using electric explosion of conductors and carrying out structural analysis of the fracture surfaces.

Conductor is placed in the elastomer of cylindrical shape, which is then evaporated during the passage of electric current from the charger through conductor in wire explosion technique. The energy of the expanding plasma is transmitted to ring sample through the elastomer, in which cylindrical shock wave is formed. In this loading method, the complexity is to determine the radial pressure on the inner surface of the ring. In this paper, this difficulty is overcome by measuring the specified pressure using a specially designed piezosensor.

A limitation of this method is the life time of elastomer, i.e. it is destroyed under the electric explosion of conductor. For this purpose, an elastomer material was selected that it could withstand multiple exposures. Three materials were chosen: caprolactan, fluoroplastic and polymethyl methacrylate (PMMA). The most perspective material turned out to be fluoroplastic.

2. Materials and experimental technique

The aluminum rings of varying thickness and widths were used as test samples. The experiments were performed on the generator of short voltage pulses that provides the formation of electrical voltage with amplitudes (10-22) Kv. Fig. 1 shows an electrical circuit of sample loading. Capacity of charged capacitor was 0.5 microfarads.

![Diagram](image-url)

Fig. 1. Installation scheme: 1 - auto-transformer; 2 - the rectifier; 3 - charger resistance; 4 - capacitor; 5 - discharger; 6 - Rogowski coil; 7 - blasted conductor; 8 - elastomer; 9 - Oscilloscope; 10 - ring sample.
Copper wire 75 μm in diameter and with length of 40 mm was used as explodable conductor which was inserted into a cylindrical elastomer 17 mm in diameter and with length of 30 mm. With the help of piezosensor pressure was determined on the outer cylindrical surface of the elastomer and on the outer surface of the ring. Thus, it was possible to determine the pressure in the ring of \( p(t) \), and by the Laplace equation \( \sigma(t) = \frac{p(t) \cdot R}{h} \) (where \( R \) - radius of the ring, \( h \) - the thickness) - the circumferential stress \( \sigma(t) \). It was determined the threshold stress of the destruction of the ring, when there was one break. The rate of deformation was determined \( \frac{d\varepsilon}{dt} \) on stress pulse front.

Electric explosion of conductor (EEC) was controlled by a current oscillogram. Fig. 2 shows a typical oscillogram of the current flowing through a conductor under EEC, and pressure pulse corresponding to explosion of conductor.

![Typical current oscillograms](image)

Fig. 2. Typical current oscillograms (1), passing through the explodable conductor and signal from the piezoelectric converter (2) during EEC in PMMA.

Aluminum ring samples fracture surfaces after tests were studied at the optical microscope Axio-Observer-Z1-M in a dark field. The quantity of shear fracture (Shear, %) was determined by the formula Shear = 100 - \( X \) (GOST30456-97) wherein \( X \) - fragile component area was determined by measuring the area of brittle fracture on the photograph. Microhardness was determined using hardness device SHIMADZU HMV-G by Vickers method. The structure was studied in cross-sections after appropriate etching.

3. Results and discussion

Three aluminum rings were subjected to destruction test: 1 - 18.1 mm in outside diameter, 17.5 mm in inner diameter, width 1.5 mm (explosion of conductor in kaprolaktan cylinder); 2 - 19.0 mm in outside diameter, 18.2 mm in inner diameter, width 1.0 mm (explosion of conductor in PMMA cylinder); 3 - 17.4 mm in outside diameter, 16.9 mm in inner diameter, width 1.2 mm (explosion of conductor in the fluoroplastic).

Table 1 summarizes the experimental data on amplitude values of radial pressure and circumferential stress in the elastomer at different distances from the cylinder axis, and the strain rate in the elastomer and aluminum ring.

<table>
<thead>
<tr>
<th>Elastomer</th>
<th>L, mm</th>
<th>P_re, MPa</th>
<th>σ_ce, MPa</th>
<th>P_cr, MPa</th>
<th>dε/dt, 10^4</th>
<th>1/s</th>
<th>δAl, %</th>
<th>Shear, %</th>
<th>S, mm²</th>
<th>D_g, μm</th>
<th>HV, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluoroplastic 981,3</td>
<td>25,2</td>
<td>34,0</td>
<td>25,0</td>
<td>25,0</td>
<td>33,0</td>
<td>14,5</td>
<td>119,0</td>
<td>80,9</td>
<td>0,4</td>
<td>22,7</td>
<td>1037,0</td>
</tr>
<tr>
<td>Kaprolaktan</td>
<td>29,5</td>
<td>38,5</td>
<td>34,0</td>
<td>34,0</td>
<td>37,5</td>
<td>39,7</td>
<td>149,0</td>
<td>100,0</td>
<td>0,4</td>
<td>56,1</td>
<td>2553,0</td>
</tr>
<tr>
<td>PMMA</td>
<td>33,0</td>
<td>38,5</td>
<td>34,0</td>
<td>34,0</td>
<td>37,5</td>
<td>39,7</td>
<td>149,0</td>
<td>100,0</td>
<td>0,4</td>
<td>56,1</td>
<td>2553,0</td>
</tr>
</tbody>
</table>

Table 2. Structural characteristics of the tested samples.

Symbols in the tables: L - distance from the cylinder axis, P_re - radial pressure in the elastomer, \( \sigma_{ce} \) - circumferential stress in the elastomer, P_cr - circumferential pressure in the ring, \( \frac{d\varepsilon}{dt} \) - strain rate, \( \delta_{Al} \) – elongation of aluminum ring after testing, Shear - % fiber fracture, S – aluminum sample cross-section, D_g – grain size, HV – microhardness.

Here are some comparative characteristics of the method of electrical explosion of conductors (this work) and magnetic-pulse method [Morozov et al. (2014)] for the deformation and fracture of ring specimens. EEC method allows somebody to deform and destroy samples of a larger cross-section compared to the magnetic pulse method due to generating large mechanical stresses. However, cylindrical elastomers can withstand one exposure (PMMA caprolactan) or several (fluoroplastic), which requires frequent replacement. The disadvantage of the method EEC
should be attributed the difficulty of determining the moment of the samples destruction, which is important for the dynamic testing of materials.

Table 1. Results of experiments on the explosion of conductors.

<table>
<thead>
<tr>
<th>Elastomer material</th>
<th>L, mm</th>
<th>P&lt;sub&gt;cr&lt;/sub&gt;, MPa</th>
<th>σ&lt;sub&gt;ce&lt;/sub&gt;, MPa</th>
<th>P&lt;sub&gt;cr&lt;/sub&gt;, MPa</th>
<th>dε/dt, 10&lt;sup&gt;4&lt;/sup&gt;, 1/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMMA</td>
<td>29,5</td>
<td>56,1</td>
<td>2553,0</td>
<td>-</td>
<td>2,9</td>
</tr>
<tr>
<td></td>
<td>37,5</td>
<td>40,3</td>
<td>1830,0</td>
<td>-</td>
<td>1,8</td>
</tr>
<tr>
<td></td>
<td>51,5</td>
<td>22,7</td>
<td>1037,0</td>
<td>-</td>
<td>0,99</td>
</tr>
<tr>
<td></td>
<td>38,5</td>
<td>39,7</td>
<td>-</td>
<td>181,1</td>
<td>0,4 (ring)</td>
</tr>
<tr>
<td></td>
<td>16,5</td>
<td>149,0</td>
<td>10000,0</td>
<td>-</td>
<td>7,5</td>
</tr>
<tr>
<td>Fluoroplastic</td>
<td>25,2</td>
<td>119,0</td>
<td>8083,0</td>
<td>-</td>
<td>6,0</td>
</tr>
<tr>
<td></td>
<td>34,0</td>
<td>80,9</td>
<td>5467,0</td>
<td>-</td>
<td>3,8</td>
</tr>
<tr>
<td></td>
<td>25,0</td>
<td>14,5</td>
<td>-</td>
<td>981,3</td>
<td>0,9 (ring)</td>
</tr>
</tbody>
</table>

The data of structural studies are presented in Table 2.

Table 2. Structural characteristics of the tested samples.

<table>
<thead>
<tr>
<th>Elastomer material</th>
<th>P&lt;sub&gt;cr&lt;/sub&gt;, MPa</th>
<th>dε/dt, 10&lt;sup&gt;4&lt;/sup&gt;, 1/s</th>
<th>δ&lt;sub&gt;Al&lt;/sub&gt;, %</th>
<th>Shear, %</th>
<th>S, mm&lt;sup&gt;2&lt;/sup&gt;</th>
<th>D&lt;sub&gt;gr&lt;/sub&gt;, μm</th>
<th>HV, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaprololkan</td>
<td>29,5</td>
<td>2,1</td>
<td>98,6</td>
<td>0,45</td>
<td>0,52</td>
<td>79,4</td>
<td></td>
</tr>
<tr>
<td>PMMA</td>
<td>181,1</td>
<td>0,4 (ring)</td>
<td>95,4</td>
<td>0,4</td>
<td>0,55</td>
<td>93,3</td>
<td></td>
</tr>
<tr>
<td>Fluoroplastic</td>
<td>981,3</td>
<td>0,9 (ring)</td>
<td>86,4</td>
<td>0,3</td>
<td>0,39</td>
<td>80,9</td>
<td></td>
</tr>
</tbody>
</table>

The presented data show that aluminum sample, using kaprololkan as elastomer, experiences the greatest elongation. The greatest embrittlement (the least amount of fiber in the fracture surface) is observed in the aluminum sample loaded at the highest rate of deformation and the greatest circumference pressure in the ring (the test with the elastomer - fluoroplastic).

Fig. 3 shows the fracture surfaces of the three tested with different elastomers aluminum rings.

![Fig. 3. The fracture surface of aluminum rings: (a) caprolactan elastomer; (b) PMMA elastomer; (c) fluoroplastic elastomer.](image)

It is seen the cup ductile fracture and sometimes cracks, and facets and chipped brittle fracture (Fig. 3c), which is consistent with the data presented in Table 2, when Al ring was tested with fluoroplastic elastomer, the least amount of fibers in the fracture surface one can be observed.

Fig. 4 is presented a cross-sectional structure of the same three rings tested with different elastomers.
4. Conclusions

Thus, the study showed the following:

1) Electrical explosion of conductors is quite suitable for the study of the deformation and fracture of the ring specimens at strain rates of $\sim 10^4$ 1/c;

2) Among three used materials, in which an electrical explosion of conductors was produced, the most suitable appeared to be fluoroplastic, both in terms of re-usable, and to generate higher amplitude of voltage pulses;

3) Most embrittlement occurs in aluminum sample loaded at the maximum strain rate and at the maximum circumferential pressure in the ring (when tested with the elastomer - fluoroplastic);

4) The most developed dynamic recrystallization and maximum hardness was found in an aluminum sample when tested with the PMMA elastomer.

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References


