HIGH-RATE FRACTURE OF THIN-WALLED TUBES MADE OUT OF SOFT STEEL

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UDC 539.375.5

The study of the deformation and fracture of thin-walled tubes under the action of an explosion permits obtaining information on the plasticity of a material at loading rates of 10^4–10^5 sec^{-1}, which are difficult to obtain by other methods. Thus, it has turned out that for the instant of fracture the value of the relative strain $\varepsilon = (R - R_0)/R$ (where R and R_0 are the instantaneous and initial values of the outer radius of the tube) for soft steel has a maximum at a value of the true strain rate of $\dot{e} \sim 10^4$ sec^{-1} ($e = \ln(R/R_0)$) [1]. The maximum of the dependence $\varepsilon = f[\log(\dot{\varepsilon})]$ has a definite physical meaning and can be explained from the standpoint of an energy approach to the fracture phenomenon [2]. The unusual nature of the results obtained in [1] for the steel widely used in technology required performing additional investigations. Measures are adopted in this paper to obtain an explosive action which is more uniform than in [1], and additional methods of investigation are applied. Simultaneously, new information is obtained in the tests about the peculiarities of explosive fracture of tubes and about the characteristic number of fragments (n) into which a radially expanding tube (or ring) made out of soft steel is fractured, and an attempt at a mathematical description of the phenomenon is made.

The organization scheme of the tests is similar to that described in [3]. An explosive charge was detonated in a tube made out of the material under investigation. In this research charges of cylindrical shape positioned coaxially with the tube were used. The explosive charges were fabricated as a casting out of a melt of 50% (by weight) trinitrotoluene and 50% hexogen (TH 50/50). Charges 11 mm and less in diameter ($\varphi_{\exp}$) were made out of plastic explosives based on PETN, which is energetically equivalent to TH 50/50 but has a significantly smaller critical diameter than does TH 50/50. The triggering of a charge mounted coaxially in a tube was accomplished from one end synchronously with intensification charges. Measures to decrease the effect of the mounting details were taken in the installation of the charges in the tubes, and it was borne in mind that any inertial detail near the explosive can significant intensify and distort fracture of the tube.

Tubes made out of steel 20 with a length of five diameters were used in the tests. In the majority of the tests the tube diameter (ϕ) was equal to 42 mm, and in part of the tests ϕ = 105 and 426 mm. The relative thickness of the wall of the tubes was δ = 4.2–4.6%. The surface of the tubes was cleaned of oxides prior to a test in order to avoid an advancing dust cloud upon their explosive expansion.

Recording of the expansion and fracture process of the tubes was performed by several methods. Tests 1–15 were done by the photographic method – two synchronously operating devices (a streak camera in regimes of photorecording (shadow method) and time loop) is estimated to be 5–10%. Tests 16–24 were done by the pulsed radiography method, which permitted obtaining direct information about the number (or characteristic size) of the fragments formed in the tube cross section as well as observing the overall fracture pattern of the tubes. Fragments of the tubes were captured in tests 25–32 by decelerating them in sawdust. The accuracy of the determination of the number of fragments is estimated to be ±10%. The test results and some initial data of the experimental assemblies are given in Table 1 and the graphs. The dependences of the radial disintegration velocity of the tubes v_1 prior to fracture (curve 1) and the velocity of the explosion products v_2 after fracture (curve 2) are plotted for tests 1–15 in Fig. 1 as a function of the ratio of the running masses of the explosives and the tube m. The values of v_1 refer to the rupture times of the tube and the motion of the fragments by inertia. A comparison of the dependence $v_1(m)$ with a similar dependence obtained in [4] with the differences in the explosives taken into account indicates their good agreement (±5%). A similar comparison with the data of [5] reveals a discrepancy of the results evidently caused by the absence of gaps between the explosives and the tube in [5]. The values of v_1 are similar in our tests ($m \sim 1$) for small gaps.

The dependence $\varepsilon_f(\log \dot{e})$ is plotted from the data of tests 1–24 in Fig. 2 (1–3 photochronographic tests with tubes having ϕ 42, 105, and 426 mm, respectively, and 4-radiographic tests with tubes having ϕ 42 mm).

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 112–117, January–February, 1983. Original article submitted June 23, 1981.

TABLE 1

Test No.	m	ϕ_{exp}, mm	ε_f, %	n, pieces	Test No.	m	ϕ_{exp}, mm	ε_f, %	n, pieces
1	0,09	8	47		17	0,13	10	44	30
2	0,13	10	62		18	0,30	15	66	50
3	0,13	10	53		19	0,82	24,5	84	
4	0,16	11	59		20	0,83	24,5	77	70
5	0,34	16	68		21	1,32	30	71	80
6	0,34	16	73		22	1,31	30	67	80
7	0,56	20	70		23	2,04	37,5	60 (15)	
8	0,82	24,5	78		24	1,37	~30,5	62 (28)	
9	1,30	30,5	65		25	0,05	6		10
10	1,36	30,5	48		26	0,087	8		21
11	1,81	35	35		27	0,13	10		22
12	1,74	35	50		28	0,34	16		33
13	0,76	24,5	88		29	0,56	20		60
14*	0,33	160	36		30	0,82	24,5		63
15†	0,13	24,5	42		31	1,32	30		67
16	0,13	10	50		32	2,04	37,5		69

* — ϕ = 426 mm; † — ϕ = 105 mm.

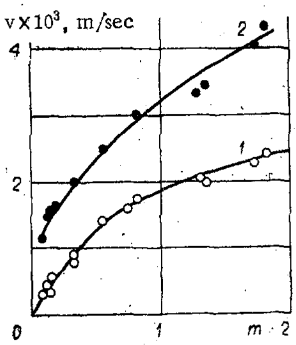

Fig. 1

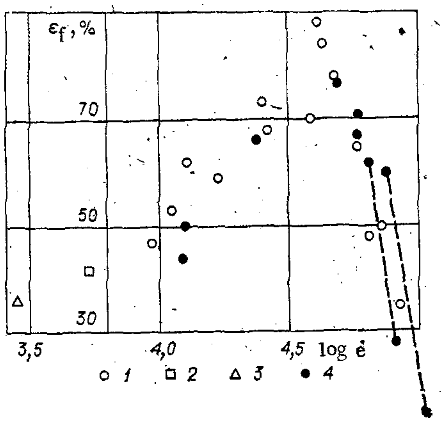

Fig. 2

The values of $\dot{e}$ were calculated for the times of tube fracture according to the formula $\dot{e} = v_1/R = v_1/[(1 + \varepsilon_f)R_0]$, where the values of v_1 were found from the set of tests from the plot of Fig. 1. The experimental data $\varepsilon_f(\log \dot{e})$ obtained by the different methods are not contradictory. Just as in [6], when $\dot{e} < 10^4$ sec^{-1} the value of ε_f increases as $\dot{e}$ increases. When $\dot{e} > 10^4$ sec^{-1}, as in [1], the experimental data indicate the existence of a maximum, although the location of the latter is shifted somewhat in the direction of higher values of $\dot{e}$ ($\log \dot{e}_{max} \sim 4.6$) and the amplitude is increased ($\varepsilon_{max} \sim 0.8$), but the $\varepsilon_f(\log \dot{e})$ dependence itself has an asymmetrical form.

The difference of $\varepsilon_f(\log \dot{e})$ from the analogous dependence obtained in [1] is not unexpected. A change in the shape of the charge has made the disintegration process of the explosion products more similar to a one-dimensional one and lengthened the effective acceleration time of the tube [7]. Therefore the assumption of instantaneous acceleration of the tube which was adopted in [1] in the derivation of the formula $\varepsilon_f(\log \dot{e})$ is too crude for this research. The theory developed there requires refinement with respect to the experiments in question. This refinement should take into account not only the action of the explosion products, which accelerate the tube walls, but also the concurrent process of energy dissipation due to plastic flow of the material.

The use of cylindrical explosive charges has led to a noticeable change in the energy sampling coefficient, which is defined as the ratio of the maximum kinetic energy of the disintegrating tube to the energy of the explosives. If this coefficient was 0.32 for charges of spherical shape [3], then it increased to 0.42 for charges of cylindrical shape ($m > 0.5$).

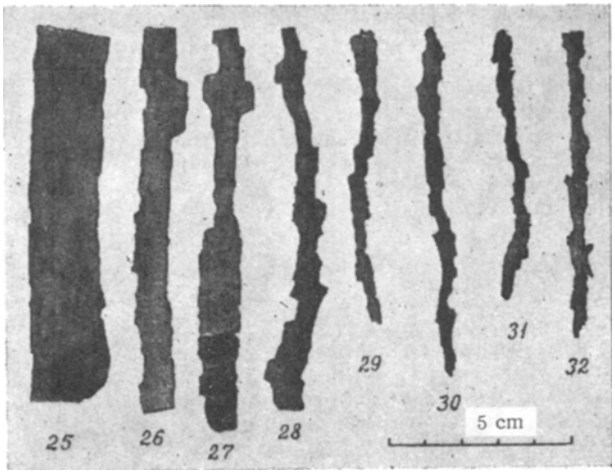

Fig. 3

Some of the typical fragments obtained in tests 25-32 are shown in Fig. 3. The number of fragments (n) was defined as the ratio of the specific (per unit length) mass of the tube to the analogous average value of the mass of a fragment.* The specific value of the mass of a fragment was found by dividing its mass by its length.

Pulsed radiography permitted revealing some details of the fracture of tubes. Characteristic radiographs of two tests with significantly different values of v_1 are given in Fig. 4 (test 23) and Fig. 5 (test 17). The initial positions of the tubes are plotted as dashed lines. It turned out that when large explosive charges were used ($m > 0.2$) fracture of a tube is accompanied by separation from the end of the tube of a narrow annular region of material moving at a lower radial velocity than does the rest of the tube. The separation of the ring is evidently caused by the outflow of an oblique shock wave (due to unloading of the shell from the end) towards the outer edge of the tube, and as a consequence of this, the collision of rarefaction waves propagating from the end and the outer lateral surface of the tube. A ring disintegrating into 35-40 fragments is clearly visible in Fig. 4 (region c-d). In contrast to the main mass of the tube, the fragments of the ring have no tangential component but are flying apart radially with a velocity ~ 1.5 km/sec. Fragments of the main mass of the tube are oriented along the generatrix of the tube (Figs. 4 and 5).

When $v_1 < 2.2$ km/sec, the front of propagating cracks is localized in a rather narrow region of values of $\Delta\varepsilon \sim 5\%$. As v_1 increases, two-three leading cracks (K and M in Fig. 4) are recorded in addition to the usual front of numerous cracks (tests 23 and 24, $v_1 = 2.52$ and 2.18, $\varepsilon_f = 60$ and 62%). Leader cracks were observed for $\varepsilon_f = 15\%$ (test 23) and 28% (test 24). The values of ε_f for the leader cracks are given in parentheses in Table 1. Points corresponding to the main and leader cracks of tests 23 and 24 in Fig. 2 are connected by dashed lines.

Thus from some values of v_1 the fracture mechanism proves to be a two-stage one. What are the reasons for the origin of leader cracks? Those which have been predicted in the case of brittle fracture [13], or are other ideas necessary for their explanation? It is not clear. Since the propagation processes of detonation in a column of explosives, deformations of the tube, and propagation of a crack front are steady-state processes (at least at distances greater than 1.5-2 tube diameters), propagating at a velocity $D = 7.65$ km/sec, it is evident that the advance of cracks is a forced supersonic process (in Fig. 4 CD is the detonation wave, front, and a-b is the region of acceleration of the tube).

It is useful for an understanding of the nature of the formation of fragments upon the fracture of tubes and for obtaining semiquantitative dependences to describe the phenomenon mathematically, even if only in a first approximation. Let us consider a ring (tube) expanding with a constant radial velocity v_1. We shall assume as in [1] that the work in breaking the material into parts (passage of a crack) is performed at the expense of elastic energy removed from the vicinity of the material in which the fracture develops. We shall also assume that fracture occurs when $\varepsilon_f \ll 1$ (actually, $\varepsilon_f \sim 1$), the material of the ring is viscoplastic $\sigma = \sigma_0 + \dot{e}\eta$ (σ and σ_0 are the dynamic and static yield stresses, and η is the viscosity of the material), and the

*The concept of a characteristic fragment size or number of them n was used in [8-10]. It has been shown in [11] experimentally and computationally (on the basis of Mott's phenomenology of fracture [12]) that the size distribution of tube fragments has a sharply expressed maximum.

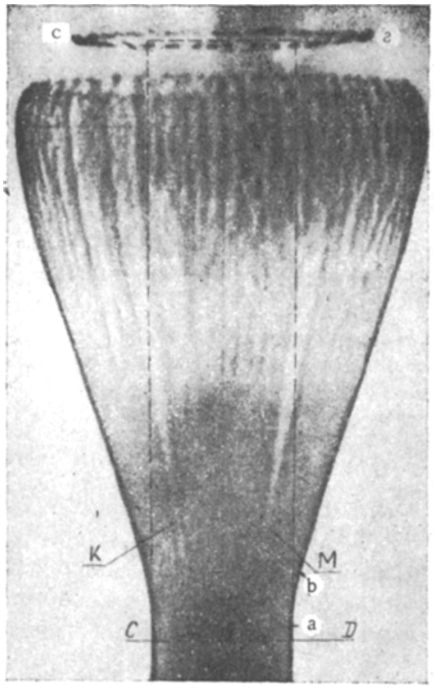

Fig. 4

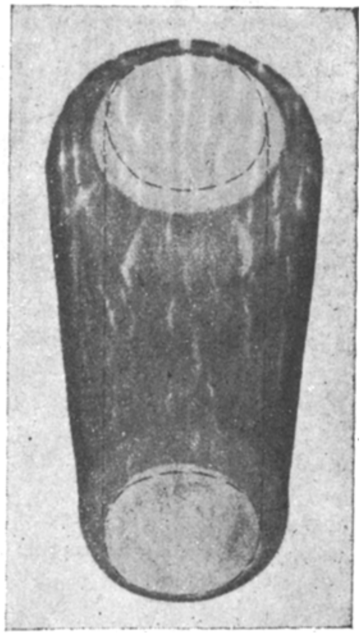

Fig. 5

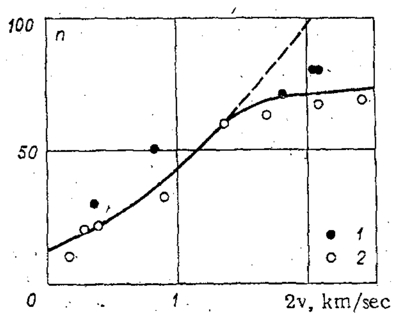

Fig. 6

value v_1 is attained instantaneously and does not decrease due to plastic stretching of the tube. According to [1], the strain upon fracture is

$$\varepsilon_f = \dot{e}\alpha/(1 + \mu\dot{e})^2 \tag{1}$$

(α and μ are constants of the material).

As in [1], we shall assume that the development of cracks throughout the wall thickness of a tube is concluded on the path from R_0 to $R = (1 + \varepsilon_f) R_0$ or

$$\varepsilon_f = (R - R_0)/R_0 = vt/R_0. \tag{2}$$

Assuming that the breaking down of the ring into equal fragments is completed by the time t when all the elastic energy is unloaded at the speed of sound into the developing cracks, the width of a fragment will be defined as $2\pi R/n = 2ct$ or

$$n = \pi R_0(1 + \varepsilon_f)/ct. \tag{3}$$

Solving Eqs. (1)-(3) together with account taken of the fact that $\dot{e} = v/R = v/[(1 + \varepsilon_f)R_0]$, we obtain $n = (\pi/c\alpha R_0)(R_0 + \mu v)^2$. According to [1], $\mu = \eta/\sigma_0$, $\alpha = 4E\lambda/(3c\sigma_0^2)$, and

$$n = \frac{3}{4}\pi\frac{(R_0\sigma_0 + v_1\eta)^2}{R_0 E\lambda} \tag{4}$$

(E, λ, and c are Young's modulus, the specific work per unit surface to fracture the material, and the speed of sound, respectively). According to Eq. (4), n is a function of the two parameters R_0 and v_1.

Within the framework of the assumptions made in the derivation of formula (4) the dependence $n(R_0) \neq$ const with v_1 = const indicates the absence of similarity upon the fracture of geometrically similar tubes of different sizes. The experimental data of [9] support this conclusion. The dependence $n(R_0)$ has the form of a curve with a minimum at $R = (\eta v_1)/\sigma_0$. A quantitative experimental check of (4) requires setting up special investigations. When R_0 = const, the dependence $n(v_1)$ has the form of a quadratic parabola. As v_1 increases, the number of fragments n increases, as was noted in [8].

This fact is also illustrated by the data of this paper given in Fig. 6 (1 – radiographic tests, and 2 – tests on deceleration of fragments in sawdust). When $v_1 < 1.4 \times 10^3$ m/sec, the experiments are satisfactorily described by the dependence $n = A(B + v_1)^2$, where A = 10.6 and B = 1.02; v_1 is in units of km/sec (dashed curve in Fig. 6). Starting from $v_1 \sim 1.4$ km/sec, the increase in the number of fragments is halted, and the value of n remains at the 60-70 level. With the same n the characteristic width of the fragments turns out to be only two-four times larger in all than their thickness, which is evidently a limitation on the further breaking up of material along the cylinder generatrix.

The investigation which has been performed has confirmed the existence of a maximum plasticity of soft steels at strain rates of $\sim 4 \times 10^4$ sec^{-1}, has permitted explaining within the framework of the energy approach the cause of the departure from similarity of the fracture of tubes into fragments and tentatively finding the form of the dependence $n(v, R_0)$, and has exhibited a possibility of the origin of leader cracks at strain rates of about 10^5 sec^{-1}. Such cracks do not fit into existing ideas about the fracture of tubes in the region of extreme plasticity.

LITERATURE CITED

1. A. G. Ivanov, "Peculiarities of explosive deformation and fracture of tubes," Probl. Prochn., No. 11 (1976).
2. A. G. Ivanov and V. N. Mineev, "A scaling criterion for brittle fracture of structures," Dokl. Akad. Nauk SSSR, 220, No. 3 (1975) (also see Fiz. Goreniya Vzryva, No. 5 (1979)).
3. A. G. Ivanov, L. I. Kochkin, et al., "Explosive fracture of tubes," Fiz. Goreniya Vzryva, No. 1 (1974).
4. A. I. Vorob'ev, M. S. Gainullin, et al., "An experimental investigation of the motion of cylindrical shells acted on by the products of an explosion in a cavity," Zh. Prikl. Mekh. Tekh. Fiz., No. 6 (1974).
5. N. N. Tarasenko, "An investigation of the motion of a tube wall under the action of the detonation products of an internal explosive charge," Fiz. Goreniya Vzryva, No. 5 (1974).
6. E. E. Banks, "The ductility of metals under explosive loading conditions," J. Inst. Met., 96, 375 (1968).
7. F. E. Allison and R. W. Watson, "Explosively loaded metallic cylinders," J. Appl. Phys., 31, No. 5 (1960).
8. E. E. Banks, "The fragmentation behavior of thin-walled metal cylinders," J. Appl. Phys., 40, No. 1 (1969).
9. V. A. Odintsov and L. A. Chudov, "The expansion and fracture of shells under the action of detonation products," Sb. Per. Mekh., No. 5 (1975).
10. V. M. Kuznetsov, "The fracture of metal rings in a plastic state," Fiz. Goreniya Vzryva, No. 4 (1973).
11. D. L. Wesenberg and M. J. Sagartz, "Dynamic fracture of 6061-T6 aluminum cylinders," Trans. ASME, Ser. E., J. Appl. Mech., 44, No. 4 (1977).
12. N. F. Mott, "Fragmentation of shell cases," Proc. R. Soc., Ser. A, 189, 300 (1947).
13. V. M. Kuznetsov, "Time-dependent propagation of a system of cracks in a brittle material," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1968).