METHODS FOR AN EXPERIMENTAL EVALUATION OF THE AXISYMMETRIC MOTION OF A TUBE WALL IN THE EVENT OF EXPLOSIVE DEFORMATION

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Methods are presented for the experimental determination of the radial velocity of a tube wall subjected to explosive deformation. The need for such a procedure is associated with the determination of a most important technological parameter in the explosive welding of metals, i.e., the velocity of collision between two metallic bodies.

Reliable information on phenomena associated with material behavior under short-term dynamic loads is extremely hard to obtain. At most, these processes last several tens of microseconds. This time factor is further complicated by the fact that within this brief time span pressures amounting to tens of thousands of atmospheres are developed. To overcome the many difficulties engendered by these factors, a specialized apparatus was developed to evaluate the true magnitude of the velocity of high-speed collisions between two metallic bodies. Bearing in mind that the deformation of the tube had to be accomplished within a range of small displacements, without reaching the destruction of the tube material, and that it was in this segment that we had to establish the rate of the radial displacement, we used a high-speed SFR-ZL motion-picture camera, with a high resolving power, as our recording equipment.

To photograph the process, we selected a tube 200 mm in length, made of Kh18N10T steel, with dimensions 25 × 0.9, and an M3 copper tube, with dimensions of 17.5 × 2. The length of the test segment was 100-120 mm. An elongated high-explosive charge (PETN) was positioned in the tube channel in this segment; this explosive was rated for a detonation velocity of 7500 m/sec. To prevent gas penetration into the filming area, the test segment was shielded with lightweight screens on both sides. Conditions preventing the free deformation of the tube were eliminated by suspending the tube from thin threads within the filming area, which was 250 mm. The charge was initiated by heating a constantan bridge (50 μm in cross section) with 2-3 mg of lead azide. The cross section of the heating bridge was chosen to ensure the overall synchronization of the filming process. The area was illuminated with an ÉV-45 plasma light source, with a continuous-spectrum illumination brightness of $2 \cdot 10^7$ stilbs for 430 μsec. The entire process was filmed in a time-magnification procedure wherein a single frame covered a period of 0.8 μsec, while the film was exposed at a rate of 1250 thousand frames per second.

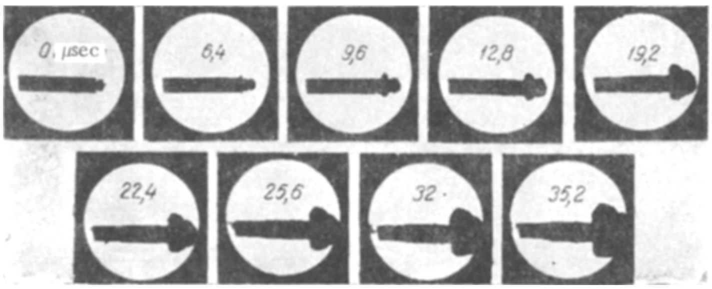

Fig. 1. Deformation of a Kh18N10T tube over a period of time, with free escape of the products of detonation.

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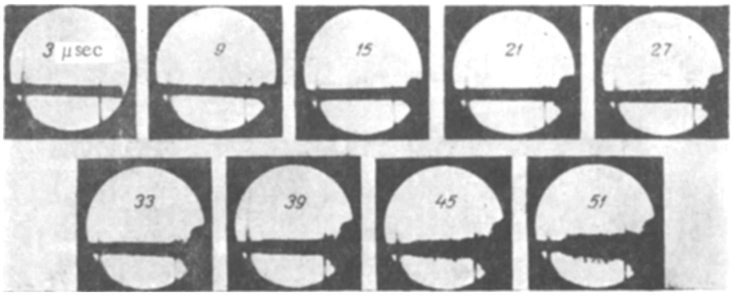

Fig. 2. Deformation of an M3 tube, over a period of time, with the discharge of the detonation products being blocked (the case of detonation proceeding from a wall).

Figure 1 shows a sequential series of typical frames (the total number of frames in the two rows is 132) for the deformation of a tube made of Kh18N10T steel, with dimensions of 2.5×0.9. At the instant $t = 0$ the explosive had not yet detonated. Within 3.2 μsec the explosive charge had been subjected to an initiating pulse and a detonation wave begins to propagate through the explosive mass. Noticeable displacement of the initial cross section of the tube appears within 9.6 μsec, from the side on which the charge is initiated. The maximum velocity in this cross section is reached after 25.6 μsec. At the same time, the charge across sections farther removed from the initiation site begin to displace as a result of the passage of the detonation wave. At $t = 12.8$ μsec the tube assumes the shape of a cone, since the cross sections of the tube more remote from the initiation site begin to move considerably later. The effect of the detonation wave at the individual cross sections of the tube subsequently increases, whereas it drops off sharply at the initial cross section because of the arrival of a relief wave [1]. On reaching the opposite end (within 19.2 μsec) the detonation wave excites an expansion wave which begins to propagate from left to right. Until both of the relief waves meet (the first moves from right to left, while the second moves toward the first) the tube-wall displacement velocity reaches its maximum within $t = 27.2$ μsec at the cross section which is situated approximately 2/3 of the way from the site of the charge initiation, and it amounts to $u = 342$ m/sec. The high-speed motion-picture frames illustrate the case of free discharge of the products of the explosion, which serves to explain the nonuniformity in the displacement of the various cross sections of the tube.

The experiment on the explosive deformation of a copper tube was performed with the products of the explosion being hindered by a barrier from escaping from the cavity of the tube. The tube was made on M3 material, and its dimensions were 17.5×2. The length of the test segment was 120 mm. The explosive was PETN, with the detonation velocity 7500 m/sec. The vertical exposure time for each frame was 3 μsec, which corresponds to a filming speed of 50 thousand frames per second. The detonation process (the formation of a dark cloud in the right-hand portion of the frame) began at the 9 μsec frame (Fig. 2). At the instant $t = 9$ μsec the near cross section of the tube feels the effect of the detonation pulse and begins to shift. The velocity in this case may be as high as 25 m/sec. At the same time, the tube segments farther removed from the site of charge initiation are in a state of rest, and the velocities in this case are equal to zero. Consequently, the tube takes on the shape of a cone. After $t = 27$ μsec, the farthest cross section – at the extreme left – will shift through a distance of 1.925 mm at an average velocity 135 m/sec. Since the discharge of the products of the explosion is hindered by a barrier in the left-hand portion of the tube, the generation and arrival of the second expansion wave is somewhat retarded, thus making it possible, during this period of time, for the tube to establish a plane-parallel moving front (the 39 μsec frame).

The tube breaks apart at the $t = 45$ μsec frame, which is seen in the strong penetration of the gas into the forming cavity. The velocity was calculated at characteristic cross sections along the tube length. The maximum radial tube-wall velocity for the case described here is $u = 240$ m/sec.

A magnetic-induction method was developed and used to record the velocities of radial tube-wall displacement over time for the case of fairly extensive high-explosive charges used in actual detonation-welding procedures.

A cylindrical shell made of a "nonmagnetic" material, in which a conductor is securely attached along the generatrix – this conductor representing the working section of a sensing element – was so positioned in a magnetic field that the displacement plane of the sensing element was perpendicular to the magnetic lines of force as the tube was deformed. An emf was induced in the working section of the sensing element. The

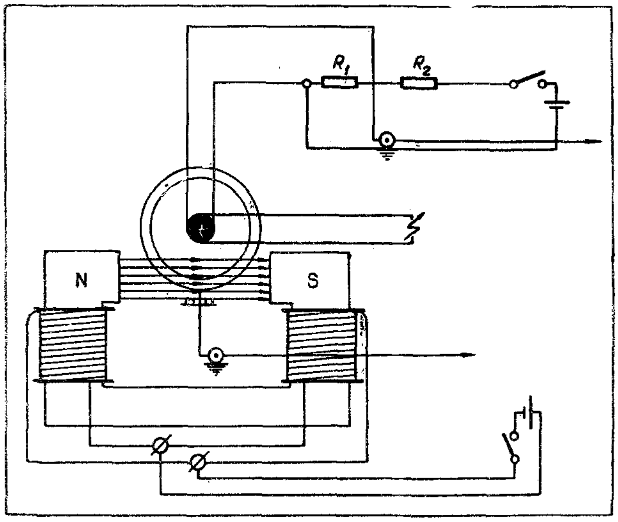

Fig. 3. Schematic diagram showing the circuit for the measurement of radial tube-wall displacement in a magnetic field.

vertical (supply) conductors remain parallel to each other as the shell is shifted, thus providing for mutual compensation of the emf's induced in them, and have no effect on the signal that arises in the working section of the sensor. After amplification, this signal is applied to the horizontal plates of the OK-17M pulsed oscillograph (Fig. 3). The sweep voltage is applied to the vertical plates. The velocity of radial shell displacement as a function of time is thus displayed on the oscillograph screen. On the linear segment of the amplitude characteristic the deflection of the beam is proportional to the magnitude of the signal applied to the amplifier:

$$\varepsilon(t) = H_0 l u(t),$$

$$r(t) = K_a K_0 K_{ph}\, \varepsilon(t), \qquad (1)$$

$$r(t) = K_0 K_a K_{ph} H_0 l u(t) = K_u u(t),$$

$$|\varepsilon| = \frac{d\Phi}{dt} = Bl\frac{dR}{dt} = Blu. \qquad (2)$$

The field intensity H_0 in the gap is numerically equal to the magnetic induction, and it is a function both of the design and of the magnitude of the current passing through the electromagnet winding,

$$H_0 = \frac{\Phi}{S} = \frac{0.4\pi NI}{\frac{l_1}{\mu} + l_0} \simeq \frac{0.4\pi NI}{l_0}, \qquad (3)$$

$$\frac{l_1}{\mu} < l_0.$$

For an exact determination of K_u without knowing all the parameters of which it is a function, we employed the following method. A micrometer screw was set up at a precisely fixed distance from the segment of the tube housing the sensor to stop the displacement of the tube. The instant that the tube collided with this barrier was recorded on the oscillogram by a pronounced reduction in beam deflection, corresponding to a rapid drop in shell displacement velocity. The calculation of K_u was thus reduced to measurements on the oscillogram and to knowledge of the gap magnitude Δ and the sweep duration T_s

$$\Delta = \int_0^{T_0} u(t)\,dt = \int_0^{l} \frac{r(l)}{K_u}\frac{dl}{K_t} = \frac{S}{K_u K_t}, \qquad (4)$$

where $S = \int_0^{l_0} r(l)dl$ is the area on the oscillogram determined by planimetry, bounded by r(t) and the zero line between the start of the process ($l = 0$) and the instant of the pronounced drop in velocity $l = l_0$; K_t is the time factor equal to $10K_{ph}/T_s$.

Finally, for the determination of K_u we find

$$K_u = \frac{S}{\Delta K_t}. \qquad (5)$$

We chose 100 mm tubes of various metals for our experiments. The load was applied through the explosion of an elongated cylindrical high-explosive charge coaxially positioned in the tube channel. The tubes were deformed in the following sequence: unilateral initiation of the explosive charge, with the axial discharge of the gas free and open.

Figure 4 shows characteristic velocity oscillograms for explosive deformation in various tubes. On the whole, these experiments can be interpreted in the following manner.

The initial sharp rise in velocity occurs at the instant that the initial pulse and limited deformations of the tube make themselves felt. The external pressure acting on the tube walls significantly exceeds the

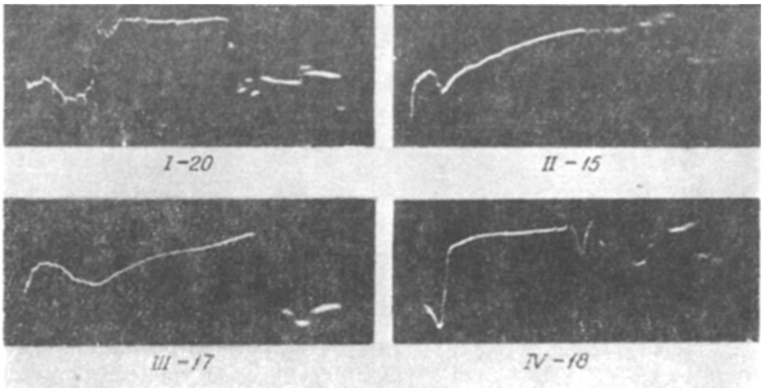

Fig. 4. Characteristic velocity oscillograms for explosive deformation.

pressure needed to overcome the resistance of the metal to plastic deformation. During the first stage the metal is therefore subject to a high rate of deformation, reaching hundreds of meters per second. This rate corresponds to the initial stage of deformation, as a result of which the first stage is accompanied by the development of high accelerations. Subsequently, with increasing deformation, the resistance increases and, consequently, there is an increase in the specific work of deformation. This phenomenon is found to occur right up to the instant at which the material reaches its ultimate strength.

The high velocities and accelerations of the metal particles which develop in high-speed deformation cause the inertial forces to assume significant importance in the process. Additional stresses arise within the metal, and in terms of their magnitude they are comparable to the stresses which arise on plastic deformation [2]. The nature of the velocity function over the passage of time for tubes of the indicated geometry depends strongly on the strength properties of the materials being deformed.

The difference in the kinetic energies, which corresponds to the instant at which the maximum tube velocity is attained with and without weakening of the cross section, determines approximately the energy of deformation, and this, in terms of absolute magnitudes, corresponds to the energy of static tube deformation.

NOTATION

B	is the magnetic induction;
l	is the length of the working section of the sensor;
u	is the displacement velocity;
K_a	is the signal amplification factor;
K_0	is the oscillograph sensitivity;
K_{ph}	is the magnification factor, equal to the ratio of beam deflection on the oscillograph screen;
r	is the magnitude of beam deflection on the screen;
N	is the number of turns in the electromagnet winding;
I	is the electromagnet supply current;
l_1	is the length of the iron core;
μ	is the magnetic core permeability, which is a function of the grade of iron and of the current magnitude;
l_0	is the air gap.

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