Formation of quasispherical converging implosion shock wave upon the reflection of an annular shock wave from a solid

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A new type of implosion has been observed experimentally: the formation of a quasispherical converging shock wave upon the reflection of an annular shock wave from a solid. The conversion of the annular shock wave into a quasispherical converging shock wave intensifies the local implosion properties.

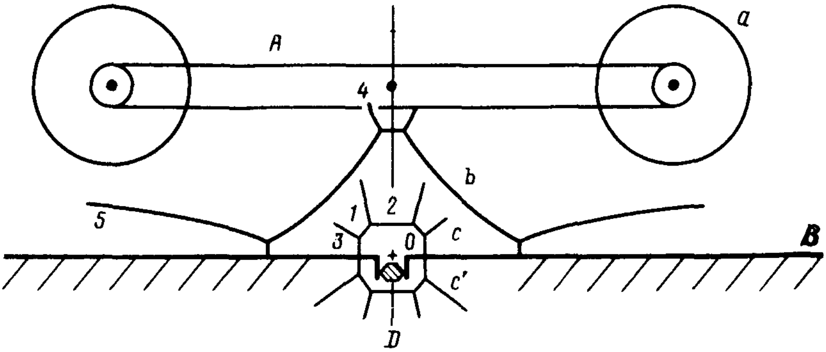
Converging shock waves have been the subject of numerous publications. The most interesting fact is that during the convergence of axisymmetric shock waves (e.g., spherically or axially symmetric,[1–3] annular,[4–6] and conical[7]) the intensity of the shock wave increases (an implosion occurs) as the wavefront approaches the symmetry axis (inversion center).

An implosion of a new type has been observed in the present experiments: the formation of a quasispherical converging wave upon the reflection of an annular (or toroidal) shock wave from a solid surface. This conversion of an annular shock wave into a quasispherical converging shock wave—a conversion observed for the first time in these experiments—results in an intensification of the local implosion properties.

It is known that a spherical converging wave is governed by the strongest implosion law, but it is unstable with respect to perturbations of its shape,[8,9] while an annular wave is fairly stable experimentally.[10] The realization of a quasispherical converging shock wave with a pronounced concentration of energy, in a geometry which is far from spherical, is accordingly a new and important result.

Figure 1a shows the experimental layout. The shock wave is excited in air at atmospheric pressure by an annular gas-discharge source. The major radius of the plasma toroid, at which the discharge energy is evolved, is $R_k = 5$ cm. The energy deposition is $E \lesssim 1.3$ kJ. The annular shock wave has a Mach number $M \sim 2$–3 near the axis. A (plexiglass) wall is situated at a distance $l = 1.5$–5.5 cm from the plane of the ring. The shock front is visualized by a shadow method.

As the front converges on the symmetry axis, its velocity increases (an implosion occurs).[5,6] This acceleration of the front leads to a change in the local angle which the front makes with the axis, so the reflection of the front from the axis occurs irregularly, and is accompanied by the appearance of a Mach shock wave. The latter wave propagates along the axis[11] (Fig. 1a). In addition, the reflection of the annular shock wave from the wall occurs in an irregular fashion at certain angles of incidence.[1,2] The Mach shock wave which arises upon this reflection converges on the symmetry axis (Fig. 1a).



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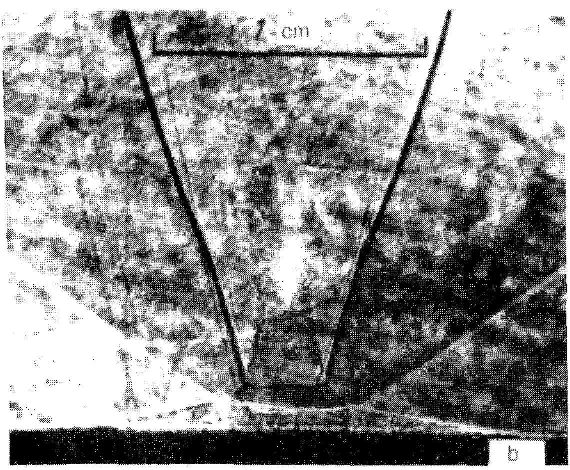

FIG. 1. a: *A*—Source of annular shock wave; *B*—solid wall; *D*—small plasticine ball; *a*—front of annular (or toroidal) shock wave at the initial time; *b,c*—converging closed configuration of shock waves at later times; *c′*—symmetric representation of configuration *c*; 1—part of front of incident annular shock wave; 2,3—Mach shock waves which arise upon the reflection of the annular shock wave from the symmetry axis and from surface *B*, respectively; 4,5—the annular shock wave reflected from the symmetry axis and that reflected from the wall, respectively. b: Shadow photographs of the fronts ($l \approx 0.7 R_k$).

The behavior of the subsequent interaction of shock fronts is determined by the relation between the radius R_k and the distance l; the most interesting case is $l \approx 0.7 R_k \approx 3.5$ cm. Figure 1b is a shadow photograph of the fronts corresponding to the time $\tau = 84$ μs. Near the point at which the symmetry axis intersects the wall (point 0), a converging configuration of shock waves forms. Here *1* is the remnant of the annular front, and *2* and *3* are the fronts of Mach shock waves which arise upon the reflection of the annular front from the symmetry axis and from the wall, respectively. A closed configuration of fronts, which we call a "quasispherical converging shock wave," converges on point 0.

We wish to stress that a quasispherical converging shock wave does not form in experiments with $l \neq 3.5$ cm.

As a quasispherical converging shock wave converges on point 0, the well-known properties of the implosion of polygonal converging fronts should be manifested.[3,12–14] For example, if the front is a regular polygonal prism, Mach shock waves arise at the corners of this prism. The growth of these waves leads to the formation of a front which has the shape of a polygonal prism whose area is smaller, and whose amplitude is higher, than that of the original wave.[3] The same process should occur in the geometry of quasispherical converging shock waves, since the observed angles between the fronts are greater than the critical angles for a transition to irregular reflection ($\sim 80°$).

We can estimate the amplification of the shock wave with decreasing front area S on the basis of the approximate Chester-Chisnell-Whitham theory:[2]

$$M \sim S^{-0,2}, \tag{1}$$

for $M \gg 1$. In the case of a cylindrical wave we would have $M \sim r^{-0.2}$, and for a spherical wave $M \sim R^{-0.4}$, where r and R are the corresponding radial coordinates.

If the Mach interaction of parts of the front of the quasispherical wave is assumed to lead to a sequential reproduction of the shape of the front with a reduced scale D, then we would have $S \sim D^2$. It follows from (1) that we have $M \sim D^{-0.4}$, as for a spherical shock wave.

In the experiments, a local burning caused by the quasispherical wave was detected. Figure 2a is a photograph of a sheet of heat-sensitive paper which was attached to the plexiglass wall and which was subjected to a single quasispherical converging shock wave. Shown for comparison in parts b and c of Fig. 2 are corresponding photographs for the values $l = 4.5$ cm (in four shots) and $l = 2.5$ cm (in three shots), respectively. In these cases the quasispherical converging shock wave did not form. We see that the thermal effect of one application of a quasispherical converging shock wave exceeds that of three or four shots at $l \neq 3.5$ cm.

Two methods were used to estimate the pressure P. The velocity of front 2 measured on the shadow photograph (Fig. 1a) near point 0 is $M \approx 3.8$. The pressure after the reflection of the quasispherical wave should increase at least as much as it does

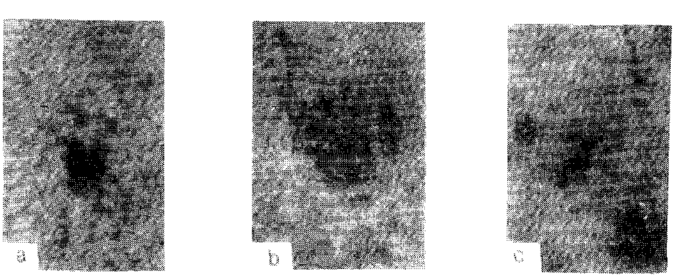

FIG. 2.

during the reflection of a plane wave from a wall. From the tables of Ref. 15 we find a lower estimate $P \gtrsim 100$ atm.

To measure the pressure and the force exerted by the quasispherical wave, we measured the velocity U of a small plasticine ball which the quasispherical converging shock wave shot out of a hole in the plexiglass wall (Fig. 1a).

This small ball was shot out horizontally from a height $H = 25$ cm. The shortest flight path in the experiments was $L_m \gtrsim 2$ m. The mass of the ball was $m = 0.13$ g, and its diameter $d \gtrsim 5$ mm. The average pressure P over the maximum cross section of the ball, $\pi d^2/4$, imparts a momentum mU to the ball in a time $\tau \sim d/c$, where $c \sim 10^3$ m/s is the sound velocity behind the reflected shock wave. We thus find

$$U > L_m\sqrt{g/2H} \approx 10 \text{ m/s}, \quad P \approx 4mUc/\pi d^3 \approx 100 \text{ atm}. \qquad (2)$$

In summary, an implosion flow of a new type arises upon the reflection of an annular shock wave from a wall in a small-scale region. The onset of this flow is accompanied by a concentration of energy and force which might find applications in the physics and technology of high pressures.

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