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To cite this article: S V Dudin et al 2019 J. Phys.: Conf. Ser. 1147 012026

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The output of a shock wave on the inner surface of a cylindrical liner

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Abstract. The results of the experimental investigations of the dynamics of the axisymmetric compression of a metallic liner are presented in this work. The studies were carried out using a high-speed camera with nanosecond resolution. It is shown that the detonation wave formed by the multipoint initiation method has a complex three-dimensional cellular structure, where first-order node lines and second-order nodes are present. The hydrodynamic instabilities formed upon the exit of the shock wave onto the inner surface of a metallic liner do not smooth out as they contract, but increase.

1. Introduction
The experimental study and numerical modeling of a cylindrical detonation wave were previously performed by the authors and the results were presented in [1–3]. The further studies have shown that during the formation of a cylindrical detonation wave by the method of multipoint initiation, the certain features on its surface and gas-dynamics flows of detonation products are observed [4]. They consist in the fact that behind the detonation wave a complex system of shock waves is formed, having a cellular structure with nodes and cords. This structure is maintained during the entire time of convergence of the detonation wave. The multi-point initiation method can be used in various explosive devices for throwing flat metal plates and for compression of cylindrical, conical or spherical shells. The output of a strong shock wave on a free surface leads to the ejection of finely dispersed particles and plasma [5, 6]. The results of the experimental recording of the surface temperature and the ejection velocities of particles and plasma are given in [6,7]. The detonation wave, which is formed by the method of multipoint initiation and having characteristic features in the form of nodes and cords [4], entering to the free metallic surface of the liner can lead not only to an increase in the ejection of particles and plasma, but also to loss of integrity of the liner because of local pressure jumps in the nodes. The study of this phenomenon is the subject of this work. It presents the analysis and results of high-speed shooting of large-scale experiments and experimental results obtained at the laboratory setup, which had been previously developed at the IPCP RAS.

2. Experimental
The difficulties of such studies are that a full-scale assembly is very elaborate and of high weight of explosive. Earlier, a simplified laboratory setup was developed and tested. The cylindrical detonation wave after the multipoint initiation was studied [1] using the laboratory setup. It
has been shown experimentally that such an assembly completely reflects all the features of the formation of a convergent cylindrical shock wave for one series of initiation points, for cross section of the full-size charge normal to the axis. Figure 1 shows the laboratory setup designed to investigate the yield of a convergent shock wave on a cylindrical liner. This assembly has 48 points of initiation of the main ring charge with a diameter of 216 mm. A metal liner, which is a thin-walled copper tube with a diameter of 90 mm and a wall thickness of 1.4 mm is located coaxial with the charge. In the center of the experimental setup, the mirror, which is inclined at an angle of 45° to the base of the assembly, is placed. It is designed to observe the inner surface of the liner when a shock wave enters it.

Simultaneous initiation of all 48 points leads to the formation of the cylindrical detonation wave with all its features, which are discussed in [4]. When it moves to the center, the shock wave exits to the liner surface and begins its axisymmetric compression by detonation products. Visualization of these processes was made using Nanogate 4BP high-speed camera (4 frames, exposition time 10 ns) and is shown in figure 2.

At the time of 41 μs the detonation wave reaches the liner surface. At the time of 43 μs one can clearly observe the formation of hydrodynamic instabilities on the inner surface of the liner,

Figure 1. The explosive device for forming the cylindrical shock wave: 1—point of initiation; 2—ring shape charge of explosive; 3—mirror; 4—metal liner.

Figure 2. Dynamics of compression of the liner at different times (the arrow shows the direction of compression).
Figure 3. The output of the shock wave on the inner surface of the liner (view through the central mirror).

Figure 4. Cell structure of cylinder detonation wave: 1—points of initiation; 2—lines of the first order nodes; A, B, C, D, E, F—the second order nodes for (a) square cell and (b) triangle cell; X axis is perpendicular to cylinder axis; Y axis is parallel to charge axis.

developing of them (45 µs) and blurring of their boundary (47 µs). All the images clearly show nodes and cords at the detonation wave and detonation products. The output of the shock wave to the inner surface of the liner from the side of the assembly axis can be observed through the mirror (see figure 1), located in the center of the assembly. This moment is shown in figure 3.

The streaks which correspond to nodes on the detonation wave front formed by multi-point initiation can be observed in the figure. It means that the nodes observed in figure 2 form the lines on the inner liner surface which are parallel to the assembly axis. We’ll term them the first-order nodes.

In the described experiments 48 initiation points were used. The long cylinder charge may be mentally imagined as a set of the ring charges. The amount of initiation points is proportional to a number of the ring charges. The initiation points can form triangle or square cells (figure 4). A flat detonation wave formed by the method of multipoint initiation is shown in figure 5. Such form of wave front is similar to one for the cylinder charge in axial cross section.

On the front of this wave the lines of interaction of detonation waves (nodes) formed by adjacent initiators are visible. As a result of this interaction the cords are observed in detonation
Figure 5. Flat detonation wave, which is formed by the method of the 4-point initiation. The arrow shows the direction of detonation propagation.

Figure 6. Dynamics of metallic liner impaction in large-scale experiment (time is measured from the moment of initiators ignition).

products. One can assume that, in a full-sized charge for a square cell configuration of initiation points, the nodes form the lines of the first order nodes in the form of circles in a plane perpendicular to the axis. The intersection of the lines of nodes of the first order inside the full-size charge will give a pattern of new points, which we call nodes of the second order.

The similar pattern was observed in the work of Inogamov and Oparin during the theoretical investigation of three-dimensional cell structures in which Richtmyer–Meshkov and Rayleigh–Taylor instabilities are revealed [8]. Earlier in the work [2] was shown that the pressure in nodes is one and a half times greater than the one in shock waves which have been formed the node. The pressure in the second order nodes seems to be even greater. During the exit of such shock wave onto the surface of metal liner the metal jets can be formed as shown in works [2, 7].

As shown above (see figure 2) for the laboratory setup, the hydrodynamic instabilities, which occurred during the shock wave exit onto the inner surface of cylinder liner, enlarge as the liner collapsed. The similar effect is observed in the large-scale experiment as shown in figure 6.

3. Conclusions

The initial stage of metal liner collapse by products of detonation, which is formed by multipoint initiation, is investigated using the laboratory setup. It has one line of initiation points and simulates a part of large-scale charge. The processes correlated with shock wave exit onto the surface of thin metal liner have been visualized using the high speed photography with 10 ns exposure time. Regular hydrodynamic inhomogeneities have been detected using axial shooting. The streaks which correspond to nodes lines on the inner liner surface have been detected using
front shooting (shooting through the mirror, which is inclined at an angle of 45° to the base of the assembly). The shooting of model process of detonation wave formation in axial cross section was carried out. Nodes and cords have been also detected. They are characteristic features of the multipoint initiation. The set of lines of the first order nodes constitutes complex three-dimensional cell structure of instabilities of shock wave during its exit onto the liner. At the intersection of the first order nodes, the second order nodes with higher parameters are formed. Such shock wave structure can result in hydrodynamic instabilities (lines of the first order nodes) and ejection of metal jets into the compressed bulk (lines of the second order nodes). During the first stage of metal liner collapse the regular hydrodynamic instabilities have been distinctly observed. They form asymmetric liner collapse and may cause ejection of metal jets into the compressing volume.

Acknowledgments

This work was supported by program of the Presidium of the RAS No. 13 “Condensed matter and plasma at high energy densities”. The work carried out on the equipment of the Interregional Explosive Center for Collective Use.

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