

STUDY OF PHYSICAL-CHEMICAL TRANSFORMATIONS IN DETONATION WAVE BY THE ELECTRIC CONDUCTIVITY METHOD

Sergey D. Gilev and Anatoliy M. Trubachev

Lavrentev Institute of Hydrodynamics, Siberian Division of Russian Academy of Sciences
Novosibirsk, 630090, Russia

Opportunities of the electric conductivity method for study physical-chemical transformations in detonation and shock waves are discussed. A measuring scheme of improved temporal resolution allows us to find a complex structure of detonation conductivity in cast TNT, TNT/RDX, and mixtures of high explosives with metals. The detonation conductivity turns out highly non-homogenous; the maximum conductivity corresponds spatially to the chemical reaction zone. Nature of conductivity for a large group of high explosives is stipulated by liberation of free carbon under exothermal chemical reaction. Results obtained lead to conclusion about the phase state and the spatial structure of the carbon particles in the chemical reaction zone and outside it. The highest conductivity is registered for mixtures HE/metal that is due to the metallic component. A temporal decrease of the conductivity for this case reflects interaction between the metal and the detonation products. The interaction depends considerably on additive content, grain morphology, and overdriving the detonation wave. The oxidation time of Al is obtained for detonation of HMX/Al mixture. Compression of the magnetic flux by the detonation wave is used for noncontact diagnostics of detonation.

INTRODUCTION

Detonation products of condensed high explosive (HE) have a noticeable electric conductivity. For most HEs the electric conductivity σ is proved to be $0.1-10 (\Omega \cdot cm)^{-1}$.¹⁻¹⁸

To explain a phenomenon of detonation conductance diverse mechanisms have been suggested (characteristic values σ are given in $(\Omega \cdot cm)^{-1}$): thermal ionization ($\sim 10^{-4} \div 10^{-5}$),¹ contact mechanism ($\square 10^2$),⁴ ionic one ($\sim 1 \div 10$),^{8,9,16} chemical ionization ($\square 1$),¹⁰ thermal emission in dense matter ($\sim 1 \div 10$),¹⁰ thermal

ionization in dense matter ($\sim 10^{-1} \div 10$).¹⁸ At present there are no recognized model of detonation conductance, which would be a prognostic tool.

Complexity of the phenomenon causes preferable development of experimental methods of investigation. The following techniques are currently used to study the detonation conductivity: the electric contact technique,^{1-5,7-12,16,17} the noncontact electromagnetic method,¹ the MHD method,⁵ the split electrode technique,^{6,12-14} and reflection of superhigh frequency radiation off a detonation front.¹⁵

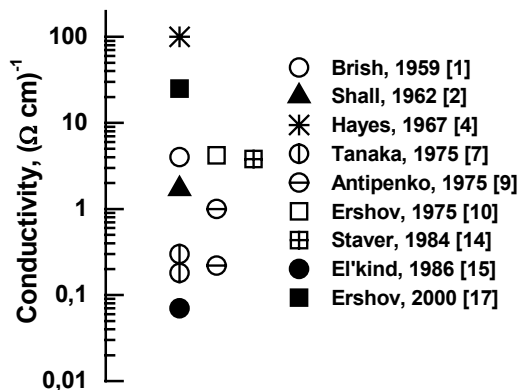


FIGURE 1. THE ELECTRIC CONDUCTIVITY OF TNT DETONATION PRODUCTS.

Although the conductivity method was used in study of detonation for almost fifty years, it did not become a routine instrument as manganin gage or laser interferometer. Using the method has been retarded by ambiguous interpretation of the records and by lack of development of experimental approaches. In our opinion, potential of the method is not realized up to now. The electric conductivity is a fine indicator of state of matter and may give valuable information on physical-chemical processes in detonation.

Present situation in this field of experimental technique can be illustrated by results for TNT. All available data on detonation conductivity of TNT are shown in Figure 1. As it is seen from the Figure, scattering of the results of different authors is about three orders of magnitude. This, firstly, testifies to serious methodical problems of measurements and, secondly, does not allow one to make reliable conclusions on nature of matter in the detonation wave. The key to understanding causes of the data contradictions lies in characteristics of measuring schemes.

This report sums up experimental development of a new measuring technique. It presents also results of using the technique to several HEs. Some details of the work may be found elsewhere.¹⁹⁻²¹

The most widespread technique for measuring the detonation conductivity is the electric contact technique. Metallic electrodes are put into tested HE. They are connected to an electric source. A detonation wave closes the electrodes and the electric current begins to flow through detonation products. This process is registered by oscilloscope as decreasing the voltage across the electrodes.

A main trouble of the measurements is unknown geometry of current spreading through the conductive region at the moment of arrival of the detonation wave at the electrode. Actually the current geometry depends on the conductivity profile, which is unknown *a priori*. The edge effect restricts severely spatial resolution and measurement accuracy. The spatial resolution is $\approx 2 \div 3 \text{ mm}$ for coaxial,^{10,12,17} ring-like² electrodes and even worse for needle ones.^{1,3,5,7-9,11} Such resolution is obviously insufficient to study the chemical reaction zone in most HEs.

Schemes of Hayes⁴ and Ershov^{6,12-14} have much better resolution. However, Hayes' scheme⁴ works only for short times and is not faultless for assumptions made. In Ershov's technique,^{6,12-14} splitting the electrode disturbs the flow and affects the measurements.

Requirements on measuring the detonation conductivity are rather specific and contradictory from the viewpoint of possibilities of an experiment. An extended charge is necessary to ensure steady detonation. At the same time, structure of current is unknown at moment when the wave shorts the electrodes. It is not possible to develop a "perfect" technique. While, a technique described below allows one to come closer to the solution of the problem.

A SCHEME OF MEASURING THE DETONATION CONDUCTIVITY

An experimental set-up on measuring the detonation conductivity of condensed HEs is shown in Figure 2. It comprises a cell incorporated in LC-circuit. Measurements are made at the maximum of the current when the current is nearly constant. A priming shock wave enters into the tested HE from a dielectric plate. Shock pressure in the HE is chosen larger than at Chapman-Jouguet plane. The voltage is registered through the electrodes connected to a shunt. The shunt (constantan foil, 100 μm thick) is put on the HE.

The present scheme has early been used for studying phase transitions in inert materials.²²⁻²⁶ It is of about one order of magnitude better temporal resolution as compared to other schemes.^{1-3,5,7-12,17} A system of electric streamlines is closer to one-dimensional; parasitic inductance in the shunt-specimen circuit is minimized. Effect of contact resistance is suppressed at measurement region; and, therefore, high conductivity (up to metallic one) can be reliably measured. Detonation wave does not deform the measuring circuit, and so no parasitic emf of induction is available. "An atonement" for these features is worse control of detonation. Restrictions of the scheme have been studied elsewhere.^{19,20}

In the framework of the electrical engineering approach, the average conductivity of detonation products can be found by the formula

$$\sigma = \frac{a_s}{a} \frac{\delta_s}{\rho_s (D-u)} \frac{1}{t} \left(\frac{V_0}{V} - 1 \right). \quad (1)$$

Here a_s is the shunt width, a is the HE width, δ_s is the shunt thickness, ρ_s is the specific resistance of the shunt, D is the detonation velocity, u is the mass velocity, V is the electric voltage, V_0 is the initial voltage.

A steady profile of the conductivity is obtained by the formula

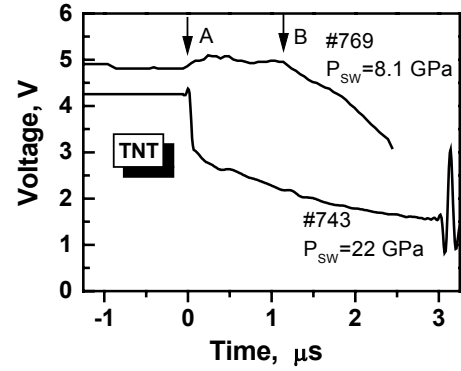


FIGURE 3. VOLTAGE RECORDS FOR DIFFERENT PRESSURES OF PRIMING SHOCK WAVE IN TNT.

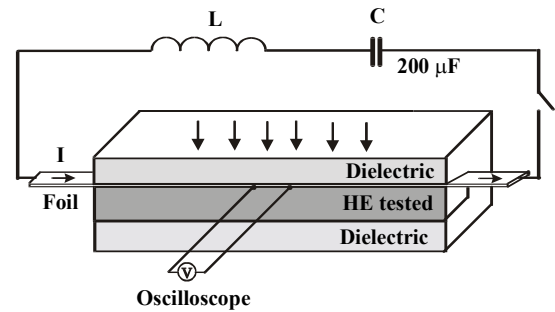


FIGURE 2. A SCHEME OF MEASURING THE DETONATION CONDUCTIVITY.

$$\sigma(t) = -\frac{a_s}{a} \frac{\delta_s}{\rho_s (D-u)} \frac{V_0}{V^2} \frac{dV}{dt}. \quad (2)$$

A basic result of using the measuring scheme is improvement of temporal resolution (up to few tenths of nanoseconds). This allows one to apply the scheme for studying fast chemical reactions in detonation and shock waves.

TNT

Two voltage records from the measuring cell filled by cast TNT are shown in Figure 3. They are obtained at different pressures P_{SW} of priming shock wave in the TNT specimen. Shock pressures P_{SW} are estimated using HE Hugoniots ($D = 2.57 + 1.88u$ for TNT).²⁷ A record at the top corresponds to a weak shock wave ($P_{SW} \approx 8.1 \text{ GPa}$) where no detonation is available for short times. A record below corresponds to an intense shock wave

($P_{sw} \approx 22 \text{ GPa}$) where one can expect detonation. A label “A” marks a moment when the shock wave enters into the TNT specimen.

As it follows from the record, small compression of the TNT does not affect appreciably the voltage. This means that conductance is absent from beginning the compression. The conductance arises at the moment $\approx 1.1 \mu\text{s}$ later (a label “B”) that points to starting reaction into the HE.

An experiment on large compression of the TNT demonstrates distinctive behavior. The Figure shows that compression of the specimen is accompanied by a sharp drop of the voltage. Note a small voltage peak at $t = 0$, which is a useful temporal marker. It rides redistribution of current in the metallic shunt during its shock compression. This testifies to occurrence of significant conductance without any noticeable delay. After the sharp decrease, the voltage changes more slowly up to arrival of the wave at a dielectric wall.

The time dependence of the voltage in the experiment #743 can be explained by occurrence of high-conductivity zone, which propagates through the specimen.

This presumption has been tested in an experiment, which used reverse direction of a wave. A shock wave enters into the TNT from below (Figure 2), propagates through the specimen, and arrives to the shunt. As specimen thickness is quite large ($\approx 20 \text{ mm}$), the detonation has to be close to the steady one. The experimental record is shown in Figure 4. A label “A” marks arrival of the detonation wave to the shunt. From this moment the electric current begins to flow up into the extended

conductive region of the detonation products, and the voltage decreases (solid curve). Figure 4 presents also a set of model curves (dotted ones) obtained from the analysis of electromagnetic diffusion in the shunt and the specimen. Modeling is taken under assumption of uniform conductivity behind the detonation front. From the Figure it is seen that later the moment “A” the voltage is much smaller than the model one. Such behavior testifies to presence of a narrow high conductive zone behind the detonation front. This zone disappears later, and the voltage is controlled by diffusion of the current into the region of detonation products. So, the experiment with opposite direction of detonation wave supports qualitatively the supposition that the high-conductivity zone propagates through the specimen.

The conductivity profile in TNT is shown in Figure 5. It is obtained in experiment #743 (Figure 3) processed by formula (2). One can see that the profile is rather complicated. Note two main parts (a peak and a plateau) with the characteristic conductivities $\sigma_1 \approx 250 (\Omega \cdot \text{cm})^{-1}$ and $\sigma_2 \approx 30 (\Omega \cdot \text{cm})^{-1}$. The evaluation of the conductivity is result of differentiation and is very sensitive to alteration of the voltage. Therefore, the conductivity σ_1 obtained at the voltage drop has to be a value of rather poor accuracy.

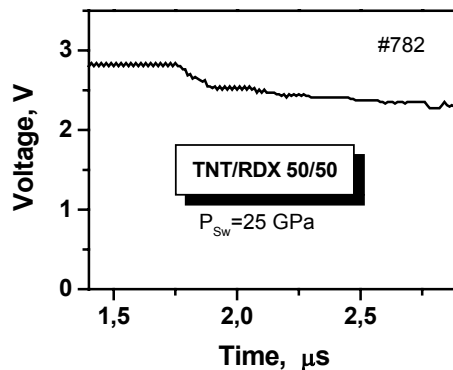


FIGURE 6. VOLTAGE RECORD FOR TNT/RDX 50/50.

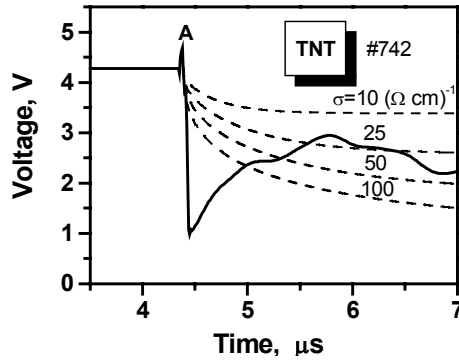


FIGURE 4. EXPERIMENTAL RECORD OF VOLTAGE (SOLID LINE) AND RESULTS OF ELECTRODYNAMIC MODELING (DOTTED LINES) FOR REVERSE DIRECTED DETONATION.

The peak conductivity σ_1 does not contradict the data of Hayes⁴ on liquid TNT. In fact, duration of the measurements⁴ did not exceed 20 ns; rising conductivity up to $\sigma_{\max} \approx 10^2 (\Omega \cdot \text{cm})^{-1}$ was recorded. This level is marked by an arrow in the Figure. A dotted line presents last Ershov's data,¹⁷ which have insufficient temporal resolution for resolving the chemical reaction zone. The plateau conductivity σ_2 corresponds well to the maximum of Ershov's data. Unlike,^{4,17} a complete profile of the conductivity is obtained by the technique proposed. The revealed structure of the conductivity allows us to explain the evident contradictions between the data in Figure 1. These discrepancies are seemingly result of several factors: complex profile of the conductivity, poor spatial resolution of most used techniques, effect of parasite inductance and resistance, lateral

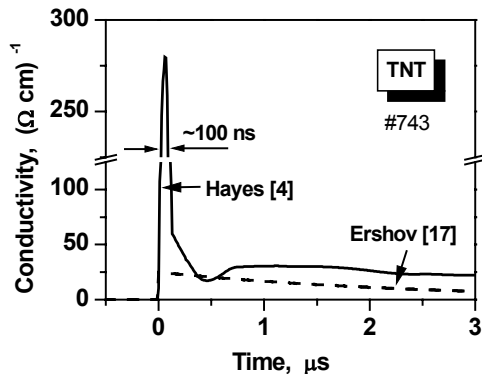


FIGURE 5. CONDUCTIVITY PROFILE IN TNT (SOLID CURVE).

rarefaction of HE, effect of specimen density, and so on.

TNT/RDX

A voltage record of cast TNT/RDX 50/50 is shown in Figure 6. The shock pressure in the specimen is about 25 GPa. The record is qualitatively similar to the TNT test and is noted for lower decrease of the voltage. The conductivity is inhomogeneous and is described by two characteristic levels $\sigma_1 \approx 35 (\Omega \cdot \text{cm})^{-1}$ and $\sigma_2 \approx 6 (\Omega \cdot \text{cm})^{-1}$.

ANALYSIS OF THE EXPERIMENTS

The evident spatial inhomogeneity is a principal peculiarity of the detonation conductivity of TNT and TNT/RDX 50/50. A region of large conductivity is attached to the wave front and corresponds spatially to the chemical reaction zone. The peak conductivities are surprisingly high. The TNT data are particularly striking. The conductivity of TNT is anomalous large among all HEs. This brings up the question: What is the nature of the phenomenon?

The high conductivity points to noticeable amount of matter with very large (almost metallic) conductivity, which is produced under the chemical reaction. Approximate content of the detonation products may be calculated in some models^{28,29} that gives commonly closed results. According to equation of state BKW, content of solid carbon at Chapman-Jouguet plane for cast TNT is $\approx 0.44 \text{ g/cm}^3$.²⁸ If carbon is of conductive phase (graphite-like), its volume content is $\approx 19\%$.

The integral conductivity of heterogeneous matter consisting of two phases with different conductivities can be estimated. The characteristic values are taken as the following: carbon in the graphite phase $\sigma_C \approx 10^3 (\Omega \cdot \text{cm})^{-1}$, its

content $\approx 19\%$, and the rest of detonation products $\sigma_{DP} \approx 1 (\Omega \cdot cm)^{-1}$. A simple model³⁰ (sphere-like well conductive particles) leads to the integral conductivity $\approx 30 (\Omega \cdot cm)^{-1}$, which closes to σ_2 . The peak conductivity σ_1 cannot be explained by this manner if even all carbon of a TNT molecule releases into the graphite phase. Such large conductivity supports an hypothesis⁴ that the conductive particles form long chains. An estimate based on a simplest model³¹ (plane conductive layers in a cubic cell) reduces to the integral conductivity $\approx 200 (\Omega \cdot cm)^{-1}$ that closes to σ_1 .

Thus, the experimental results can be explained by formation of highly conductive particles (probably graphite-like). The spatial structure of the particles may be severely differing inside the chemical reaction zone and outside it. Just after compression the particles may form a grid-like structure, which transforms later to single inclusions.

IMPORTANCE OF CARBON

The above analysis points to decisive effect of carbon on the conductivity of TNT. From this point of view it is interesting to compare TNT, TNT/RDX, and other HEs. All available data on the conductivity in the chemical reaction zone for different HEs are shown in Figure 7. Such data are only few in number; main part of the experiments¹⁻¹⁷ are of low spatial resolution and cannot resolve the chemical reaction zone. Abscissa axis is amount of solid carbon found by BKW model.²⁸ As it follows from the Figure, there is a distinct correlation between content of carbon and the conductivity in the chemical reaction zone (firstly such correlation was marked by Hayes⁴). Variation of the conductivity is about three orders of magnitude. Note, the data were obtained by different authors used diverse

measuring schemes. The Figure demonstrates intrinsic agreement between these data.

The correlation found is evidence that nature of the detonation conductivity rides by liberation of carbon. It is interesting that the dotted line in the Figure 7 intercepts the vertical axis at zero content of carbon. This testifies to another mechanism of conductivity, which is appreciable for small amount of carbon (chemical ionization, thermal ionization, ionic conduction, or others). Such mechanism can deviate the data from the uncovered dependence for small content of carbon in detonation products.

MIXTURES HE/METAL

One might expect even larger conductivity if mixtures HE/metal are studied. It makes registration more difficult. In this case, one has to take into consideration the electromagnetic skin effect in metallic conductors (electrodes, shunt) as well as in the conductive products of detonation. Structure of the electromagnetic field in a growing conductive layer is stipulated by a parameter³² $R = \mu_0 \sigma (D - u)^2 t$. The

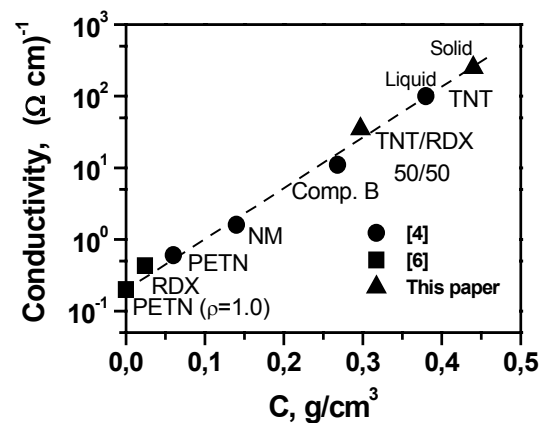


FIGURE 7. CONDUCTIVITY IN CHEMICAL REACTION ZONE VERSUS CONTENT OF SOLID CARBON CALCULATED BY BKW MODEL.

parameter is a ratio of the electromagnetic relaxation time and the propagation time of the wave.

If $R > 1$, then structure of the electromagnetic field is nonequilibrium; the skin effect interferes in the measurements. The electromagnetic field in the measuring cell is described by a system of two diffusion equations.³³ To obtain the conductivity one has to find the diffusion coefficient inside a conductive region using information from its boundary. From the mathematical viewpoint such problem is ill-posed and has no correct solution. The problem may be solved in the framework of a specified physical model. For purposes of qualitative analysis, it is useful to combine the electrical engineering approach (formulae (1), (2)) and the electrodynamic modeling with some simplified assumptions. So, for the electrodynamic model^{20,33} the mass velocity and the conductivity of matter are assumed to be uniform.

An experimental record (solid line) is shown in Figure 8 for shock compression of Al powder (grain size is $10-40 \mu m$, density is $\approx 1.65 g/cm^3$, shock pressure is $\approx 9.5 GPa$). A dotted line in Figure 8 presents a result of the electrodynamic modeling. The simulation corresponds to conductivity of compressed powder $\square 3.3 \cdot 10^4 (\Omega \cdot cm)^{-1}$. Agreement between the experimental and model lines is satisfactory. Thus, the conductivity of Al powder in shock wave is time independent.

An experimental record (solid line) is shown in Figure 9 for mixture HMX/Al 60/40 (density $\approx 1.4 g/cm^3$). The voltage drop for time interval A-B is caused by motion of a metallic plate (used as a pressure attenuator). The moment "B" corresponds to arrival of a shock wave to the HE. At this moment appreciable conductivity arises in the HE. A result of the electrodynamic modeling (dotted line) is also shown in Figure 9. The simulation is

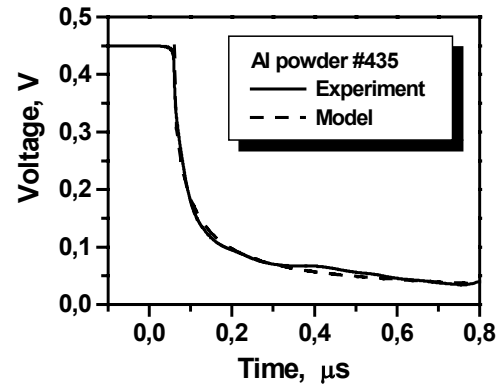


FIGURE 8. VOLTAGE RECORD FOR SHOCK COMPRESSION OF AL POWDER AND RESULT OF MODELING.

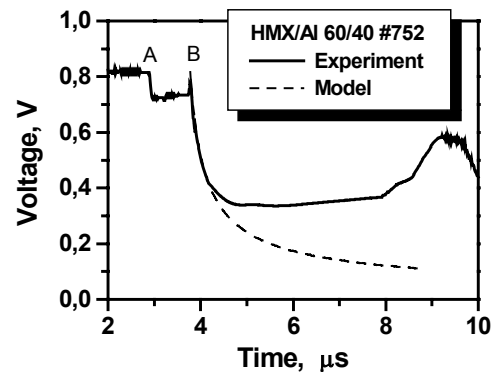


FIGURE 9. VOLTAGE RECORD FOR MIXTURE HMX/AL AND RESULT OF MODELING.

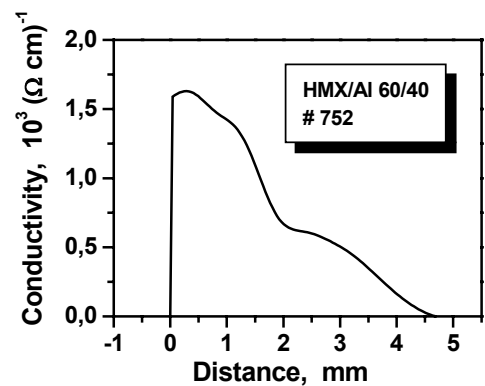


FIGURE 10. CONDUCTIVITY PROFILE FOR DETONATION WAVE IN MIXTURE HMX/AL.

performed for constant conductivity $2 \cdot 10^3 (\Omega \cdot cm)^{-1}$. From the Figure one can see that the voltage at first follows the

electrodynamic modeling and later deviates from it. Such behavior testifies to the conductivity as temporal dependent.

A conductivity profile in the detonation wave can be obtained qualitatively if one disregards electromagnetic nonequilibrium of the HE. A result of processing the experimental record #752 by means of the formula (2) is shown in Figure 10. This procedure rather under-estimates the conductivity but it gives insight into the spatial structure of the conductivity. As it is seen from the Figure, firstly, the conductivity is large and then it decreases fast. Evident distinction between the experiments #435 and #752 (Figures 8 and 9) points to interaction between Al and the detonation products. Physical picture may be drawn as the following. Under compression HE is packed, and the chemical reaction is initiated. Amount of the metal component is large and the appreciable macroscopic conductivity arises. This conductivity is of impurity nature (the conductivity of pure HMX is 3 orders of magnitude lower). The decrease of the detonation conductivity (Figure 10) testifies to chemical interaction between the components. Al oxidizes; a non-conductive film arises at surface of grains; and the integral conductivity decreases. From Figure 10 one can estimate the oxidation time of Al in the detonation wave ($\approx 0.5 \mu s$).

Such interpretation of processes in the detonation wave agrees qualitatively with data obtained by a routine manganin gage. The gage is placed at interface of a mixture HE and a dielectric. The gage registers slower temporal decrease of the pressure for the mixture HMX/Al as compared with pure HMX. This testifies to release of additional energy due to oxidation of Al. Our records do not contradict ones obtained by the optic pyrometer technique.³⁴

The conductivity experiments demonstrate qualitative similar behavior for conditions of different content of metal and grain morphology. As content of the

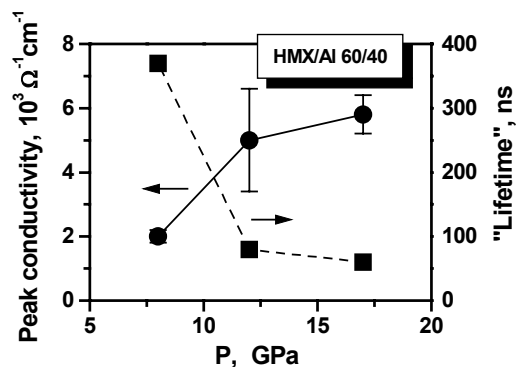


FIGURE 11. PEAK DETONATION CONDUCTIVITY AND CONDUCTIVITY "LIFETIME" VERSUS PRESSURE OF PRIMING SHOCK WAVE.

metallic additive rises, the conductivity and its "lifetime" increase too. As particle size decreases, the conductivity "lifetime" decreases too. This testifies to more intensive interaction between the additive and the detonation products.

OVERDRIVEN DETONATION

The present measuring cell allows one to study the chemical reaction for overdriven detonation. Experimental data for the mixture HMX/Al 60/40 are shown in Figure 11. Normal detonation pressure of the mixture is $\approx 8 \text{ GPa}$. One can see from the Figure that the peak conductivity increases, and thickness of the high conductive zone decreases in few times under overdriven. These profound changes are due to physical-chemical processes in the reaction zone. Increase of the pressure leads to additional compression of the matter; Al particles are closer to each other, and the conductivity rises. By virtue of higher pressure, the interaction between the components is more intensive. Therefore, the oxidation reaction runs faster; the conductivity decreases faster too. Thus, the data testify to decreasing the oxidation time of the metallic additive in overdriven detonation.

NONCONTACT DIAGNOSTICS OF DETONATION PROCESSES

Detonation of the mixture HE/metal gives products of metallic conductivity concentrated in a thin layer. Convergence of the detonation waves into such HE may increase the magnetic field at the system axis. This phenomenon is of interest for physics of detonation as a potential diagnostic tool.

An experimental set-up is shown in Figure 12. Twelve initiators form a quasi-cylindrical detonation wave in an auxiliary HE. The tested HE (HMX/Al 60/40) is placed in the center region of the device. An inductive gage is at the system axis. Initial traverse magnetic field B_0 is created before ignition. Detonation of the mixture HMX/Al results in formation of a closed configuration of waves, which captures the magnetic flux and compress it to the system axis.

A voltage record of the inductive gage (after integration) is shown in Figure 13. Such signal is proportionate to the magnetic field at the system axis. Labels "A" and "B" denote correspondingly moments of arising the conductive layer and arriving the wave at the gage. The experiment demonstrates generation of the magnetic field by detonation wave.

For sufficiently high conductivity of the detonation products, the magnetic field during compression can be obtained by the following approximate formula

$$B(t) \approx B_0 \left(\frac{S_0}{S(t)} \right)^{\frac{u}{D}}$$

Here S_0 is the initial cross section of the tested HE, $S(t)$ is the cross section of HE region bounded by the conductive layer at the moment t .

The field depends on parameters of the detonation wave. This opens up possibilities for using a phenomenon of the

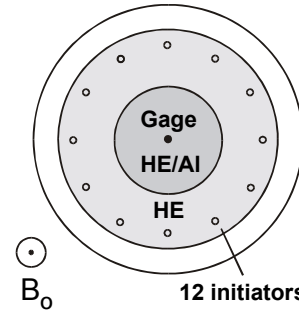


FIGURE 12. LAYOUT OF DETONATION COMPRESSION OF MAGNETIC FLUX

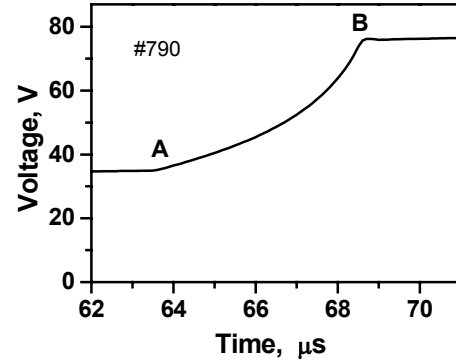


FIGURE 13. VOLTAGE RECORD IN A TEST ON DETONATION COMPRESSION OF MAGNETIC FLUX

magnetic compression for noncontact diagnostics of detonation processes. So, the compression time determines the detonation velocity, the temporal rise of the field determines compressibility that jointly reduces the mass velocity. The detonation parameters obtained by this technique ($D \approx 4.4 \text{ km/s}$, $u/D \approx 0.24$) coincide satisfactory with results of routine techniques. The compressibility is found during propagation of the wave and may be available for continuous measuring.

OPPORTUNITIES OF THE CONDUCTIVITY METHOD

The investigations demonstrate opportunities of using the electric conductivity method for studying physical-chemical transformations in shock and detonation waves. The features of the method are the following:

- the high sensibility (conductivity change at the chemical reaction zone is about an order of magnitude),
- the good temporal resolution (few tenths nanoseconds),
- data are available on the phase state of matter and the spatial structure of conductive phase,
- the time-resolved diagnostics of fast chemical reactions,
- unsteady detonation can be studied (overdriven regime, transient processes, and so on).

ACKNOWLEDGMENTS

Authors acknowledge Ershov A.P. for helpful discussions. The present work is supported partially by grant No. 02-03-32873 of Russian Foundation for Basic Research.

REFERENCES

1. Brish, A.A., Tarasov, M.S., and Tzukerman, V.A. "Electrical Conductivity of Explosion Products of Condensed High Explosives," *Zh. Eksp. Teor. Fiz.*, Vol. 37, No 6 (12), 1959, pp. 1543-1549.
2. Shall, R. and Vollrath, K. "Sur la conductibilit'e 'electrique provoqu'ee par les ondes de d'etonation dans les explosifs solides," In *Les Ondes de D'etonation*; Centre Nat. de la Recherche Sci.: Paris, 1962, pp. 127-136.
3. Jameson, R.L., Lukasik, S.J., and Pernick, B.J. "Electrical Resistivity Measurements in Detonating Composition B and Pentolite," *J. Appl. Phys.*, Vol. 35, Pt. 1, No 3, 1964, pp. 714-720.
4. Hayes, B. "On the Electrical Conductivity in Detonation Products," *Proc. 4th Symposium (Internat.) on Detonation*; Office of Naval Research, ACR-126: Washington, 1967, pp. 595-601.
5. Zinchenko, A.D., Smirnov, V.N., and Chvileva, A.A. "Measurement of the Electrical Conductivity of the Explosion Products of Cast 40/60 TNT/RDX," *Combust. Expl. Shock Waves*, Vol. 7, No. 3, 1971, pp. 364-367.
6. Ershov, A.P., Zubkov, P.I., and Luk'yanchikov, L.A. "Measurements of the Electrical Conductivity Profile in the Detonation Front of Solid Explosives," *Combust. Expl. Shock Waves*, Vol. 10, No. 6, 1974, pp. 776-782.
7. Tanaka, K. "Measurement of Electrical Conductivity in Detonation Products," *Report on 5th Internat. Colloquium on Gasdynamics of Explosions and Reactive Systems*. Bourges, France, 1975.
8. Yakushev, V. V. and Dremin, A. N. "Nature of Electrical Conductivity of Detonation Products of Condensed Explosives," *Dokl. Akad. Nauk SSSR*, Vol. 221, No. 5, 1975, pp. 1143-1144.
9. Antipenko, A. G., Dremin, A. N., and Yakushev V. V. "Zone of Electrical Conductivity in Detonation of Condensed Explosives," *Dokl. Akad. Nauk SSSR*, Vol. 225, No. 5, 1975, pp. 1086-1088.
10. Ershov, A. P. "Ionization during Detonation of Solid Explosives," *Combust. Expl. Shock Waves*, Vol. 11, No. 6, 1975, pp. 798-803.
11. Antipenko, A. G. and Yakushev, V. V. "Nature of Electrical Conductivity of Detonation Products of Condensed Explosives," In *Detonation, Proc. 5th All-Union Symp. on Combustion and Explosion, Joint Inst. Chem. Phys.: Chernogolovka*, 1977, pp. 93-96.
12. Ershov, A. P., Zubkov, P. I., and Luk'yanchikov, L. A. "Nature of Electrical Conductivity Behind the Detonation Front of Condensed Explosives," *ibid.*, pp. 89-92.
13. Ershov, A.P., Lukjantshikov, L.A., Rjabinin, Ju.V., and Zubkov, P.I. "Electrophysical Properties of Detonation Products of Condensed Explosives," In *Megagauss Physics and Technology. Proc. 2th Internat. Conf. on Megagauss Magnetic Fields Generation and Related Topics*; Plenum Press: N.Y., L. 1980., pp. 89-98.

14. Staver, A. M., Ershov, A. P., and Lyamkin, A. I. "Study of Detonations in Condensed Explosives by Conduction Methods," *Combust. Expl. Shock Waves*, Vol. 20, No. 3, 1984, pp. 320-323.
15. El'kind, A. I. and Gusar, F. N. "SHF Measurement of Electrical Conductivity Behind a Detonation Wave Front in TNT," *Combust. Expl. Shock Waves*, Vol. 22, No. 5, 1986, pp. 632-636.
16. Yakushev, V.V. "Electrical Conductivity of Shock-Compressed Liquid Dielectric and Weak Electrolytes," Report at Intern. AIRAPT Conference on High Pressure Science and Technology. Honolulu, Hawaii, USA 1999.
17. Ershov, A. P., Satonkina, N. P., Dibirov, O. A., Tzykin, S. V., and Yanilkin, Yu. B. "A Study of the Interaction Between the Components of Heterogeneous Explosives by the Electrical-Conductivity Method," *Combust. Expl. Shock Waves*, Vol. 36, No. 5, 2000, pp. 639-649.
18. Zubkov, P. I. "About Electronic Conductance of TNT Detonation Products," In V Zababakhin Scientific Reading; Proceedings, Pt. 1, RFNC VNIITF: Snezhinsk, 1999, pp. 225-227.
19. Gilev, S. D. and Trubachev, A. M. "High Electrical Conductivity of Trotyl Detonation Products," *Technical Physics*, Vol. 46, No. 9, 2001, pp. 1185-1189.
20. Gilev, S. D. and Trubachev, A. M. "Detonation Properties and Electrical Conductivity of Explosive-Metal Additive Mixtures," *Combust. Expl. Shock Waves*, Vol. 38, No. 2, 2002, pp. 219-234.
21. Gilev, S. D. and Trubachev, A. M. "Generation of Magnetic Field by Detonation Waves," *Technical Physics*, Vol. 47, No. 4, 2002, pp. 474-477.
22. Gilev, S. D. "Electromagnetic Methods for Investigation of Chemical and Phase Transformations of Solids in a Shock Wave," In *Metallurgical and Material Applications of Shock-Wave and High-Strain-Rate Phenomena*. Proc. of the Intern. Conf. Elsevier: Amsterdam, 1995. pp. 785-792.
23. Gilev, S. D. and Trubachev, A. M. "Shock-Induced Conduction Waves in Solids and Their Applications in High Power Systems," In *Shock Compression of Condensed Matter-1995*; AIP: New York, 1996; Vol. 370, Part 2, pp. 933-936.
24. Gilev, S. D. and Mihailova, T. Yu. "The Development of a Method of Measuring a Condensed Matter Electroconductivity for Investigation of Dielectric-Metal Transitions in a Shock Wave," *Journal de Physique IV*, V. 5. Colloque C3, 1997, pp. C3-211-216.
25. Gilev, S. D. and Trubachev, A. M. "A Study of Semiconductor-Metal Transition in Shocked Monocrystal Silicon," In *Shock Compression of Condensed Matter-1997*; AIP: New York, 1998; Vol. 429, pp. 777-780.
26. Gilev, S. D. and Trubachev, A. M. "Metallization of Monocrystalline Silicon under Shock Compression," *Physica Status Solidi (b)*, Vol. 211. No. 1, 1999, pp. 379-383.
27. LASL Shock Hugoniot Data, Berkeley, LA, London, 1979.
28. Mader C. L. *Numerical Modeling of Detonations*; University of California Press: Berkeley, LA, London, 1979.
29. Tanaka, K. "Detonation Properties of Condensed Explosives Computed Using the Kihara-Hikita-Tanaka Equation of State," National Chemical Laboratory for Industry, Tsukuba Research Center, Yatabe, Tsukuba, Ibaraki, Japan, 1983.
30. Dulnev, G.N. and Novikov, V.V. "Conductance of Non-uniform Systems," *Inzh. Fiz. Zh.*, Vol. 36, No. 5, 1979, pp. 901-909.
31. Odelevskiy, V.I. "Calculation of Generalized Conductance of Heterogeneous Systems. I. Matrix Two Phase Systems with Nonelongated

Inclusions,” Zh. Tehn. Fiz., Vol. 21, No. 5, 1951, pp. 667-677.

32. Gilev, S. D. and Mikhailova, T. Yu. “Current Wave in Shock Compression of Matter in a Magnetic Field,” Technical Physics, Vol. 41, No. 5, 1996, pp. 407-411.

33. Gilev, S. D. and Mikhailova, T. Yu. “Electromagnetic Processes in a System of Conductors Formed by a Shock Wave,”

Technical Physics, Vol. 41, No. 10, 1996, pp. 1029-1033.

34. Gogulya, M. F., Dolgoborodov, A. Yu., Brazhnikov, M. A., and Baudin, G. “Detonation Waves in HMX/Al Mixtures (Pressure and Temperature Measurements),” In Proc. 11th Symposium (Internat.) on Detonation; 1998, pp. 979-988.