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ABSTRACT

The paper presents results of the investigation of electric properties at the detonation of trinitrotoluene (TNT, trotyl, $C_7H_5N_3O_6$) charges with different preparation methods, structures, and densities, with the addition of glass microspheres and water. The detonation characteristics are compared with the literature data. We discuss the nature of the electric conductivity, the connection between the kinetics and conductivity, and the influence of inert additives. Most of the experimental data on the electric conductivity are presented for the first time.

I. INTRODUCTION

Currently, the working model of the detonation process is the Zel'dovich–von Neumann–Döring (ZND) model.[1–4] According to it, the detonation wave consists of the shock front, the chemical reaction zone (the chemical peak or the von Neumann spike), the Chapman–Jouguet (CJ) point, and the Taylor rarefaction wave. The Chapman–Jouguet point that separates the regions of hypersonic and subsonic flow corresponds in the ZND theory to the end of the chemical reaction zone. Much effort is devoted to the investigation of the reaction zone. However, the details of chemical reactions are still debatable.

It is well known that explosion is a highly destructive process. Its value is the release of comparatively high energy in a short time. The aggressive effect of detonation sets stringent restrictions on the investigation methods of this physical phenomenon.

The paper presents the results of the investigation on the electric properties of trinitrotoluene (TNT) charges with different structures, densities, and other conditions. TNT was synthesized for the first time in 1863 by Josef Wilbrandt and investigated in the beginning of XX century by another German chemist Heinrich Kast. TNT, the "working horse" of the World War II, is inferior to many other HEs by the explosive properties; however, it has the unique set of properties (stability, chemical inertness, production and application safety, low melting temperature, hydrophobicity, etc.), which made it the most popular explosive in XX century.[5] The term "TNT equivalent" is used in different areas of the explosion physics (equivalent by the explosion effect, propulsive capability, brisance, and energy release). The high mass fraction of carbon (0.37) made TNT the indispensable source of detonation nanodiamonds (DND) at their production from the mixture high explosive (HE) TNT + hexogen.[6–9]

Despite the long investigation history of TNT, many of its characteristics remain unexplored. The mechanism and the details of the nanodiamond formation are also disputable since the discovery. Deep understanding of this process would allow one to purposefully change the properties of DND according to the arising claims. DND in present acquired wide application, and the possibility to control their size would further widen their use.[10–12]

Another feature of TNT making it interesting for investigation is a very strong dependence of sensitivity on the charge structure. Cast and pressed charges with close thermodynamic parameters in the CJ point may have several characteristics (i.e., critical diameter) different by an order of magnitude.[13] This allows one to investigate the influence of the initial charge structure on the reaction zone kinetics, to study the mechanism of the HE sensitivity, to determine the characteristics of inhomogeneities, which lead to the efficient development of chemical reaction.

Keeping in mind the link between the electric conductivity and the carbon, the investigations of the electric properties at the explosion

of TNT charges provide new actual information useful to extend the understanding of the detonation processes and for the industrial use.

Investigation history of the electric properties of TNT is more than half century long. It started from the works[14–16] and includes the papers.[17–27] Experimental scatter of the values obtained is several orders of magnitude, from fractions to hundreds of $\mathrm{Ohm}^{-1}\,\mathrm{cm}^{-1}$. This demonstrates the necessity for a more thorough, full, and systematic investigation, which is the subject of the present work.

The experiments are carried out with TNT charges of high density, with charges of bulk density, and with water in pores. We investigate the influence of the addition of inert inhomogeneities on the electric conductivity for the high-density cast charge and for the charge of the density of $\rho \approx 1$ g/cm^3.

II. EXPERIMENTAL INVESTIGATION SETUP

Figure 1 presents the experimental setup for measuring the electric conductivity at the detonation of condensed HE. HE is placed into the thick-walled copper casing with outer diameter of 40 mm and inner diameter (the diameter of the HE charge) of $b = 8$ mm. The casing serves as the outer electrode. It consists of two parts marked **1** and **2** joined by thread. The voltage sensor (toroidal coil) **7** is placed inside the cavity. The layer of dielectric **6** is located between the parts of outer electrode; its thickness is usually less than 1 mm. The copper central electrode **3** has diameter of $c = 2$ mm; it is placed coaxial with the outer electrode. The inner electrode passes through the plexiglass plug **4** and is fixed by the copper screw **5** connected to the cylindrical casing by the thread. The mutual induction coefficient M between the contour containing HE and the coil **7** is measured in each experiment; it is approximately equal to 15 nH. The detonation is initiated by the high-voltage detonator through the plexiglass plug of special shape **8,** which has a cavity filled with hexogen.

HE is dielectric before the arrival of the detonation wave. When the detonation front touches the central electrode (shown if Fig. 1), the experimental cell that is connected parallel to the shunt R_S and is subject to the voltage V_0 starts to conduct electric current through the detonation wave moving along electrodes. Due to the increasing current and the appearing magnetic flux, a voltage pulse U appears at the coil **7**. When the detonation front passes the dielectric layer, the current switches from the part **1** to the part **2**. This results in the decrease in the magnetic flux producing a pulse of opposite polarity at the graph of voltage U. The value of conductivity when the detonation wave passes along the dielectrics is given by the following formula:

$$\sigma(x) = \frac{\ln(b/c)}{2\pi DM}\frac{U(t)}{V}.$$

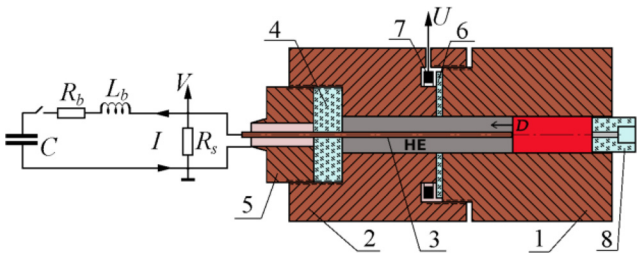

FIG. 1. Geometry of experimental cell and the supply circuit.

Here, D is the velocity of the detonation wave, x is the front coordinate at the time t, V is the voltage on the experimental cell, and M is the mutual induction coefficient between the contour containing HE and the toroidal coil. The instrumental error is about 10%. The main measurement error is associated with non-ideal detonation and charge inhomogeneity. The total error is about 20%. The details of the description of the experimental setup, numerical simulation of the cell, and the influence of the electrical conductivity distribution on the experimental data can be found in the works.[28–30]

A. Charge preparation

Experiments are carried out with cast and pressed high-density charges of TNT, with charges of density close to the bulk one, as well as with additions of hollow glass microspheres or microballoon (GMB) and water.

Fine-grained TNT is used in experiments with different structures of charges of high and bulk density and in experiments with additives. The average grain size is several tens of μm; the powder is similar to that used in the work.[13] Commercial scale TNT is ground by a pestle in a ceramic mortar. Herewith, a strong grinding occurs. However, a certain amount of relatively large particles remain, but their mass fraction is insignificant. Pressed high-density charges are produced with the hydraulic press 90 bar. For control, the punch is stopped by the restriction rings. Each pressed portion is 5 mm high.

Bulk density charges are produced by the addition of small portions of HE and slight packing under the weight of about 65 g. The charge density is determined by the mass of HE and the inner volume of the copper casing. GMB with an average size of about 58 μm and wall thickness of 1–2 μm were added to bulk and cast charges.

The main source of inhomogeneities in the preparation of cast charges is the difference between the density of liquid and crystal TNT ($\rho_{liquid} = 1.467$ g/cm^3 and $\rho_{crystal} = 1.663$ g/cm^3),[31] which leads to the formation of cavities during solidification. The tomographic investigation of cast and pressed TNT charges is presented in more detail in the work.[13] The cast charge of TNT is produced by the layered casting, which minimizes the number of inhomogeneities. For uniform cooling, the next portion is filled as a thin layer after the solidifying of the previous one. The density of cast charges is measured by the hydrostatic weighting. Several measurements are carried out for each charge, and the results are averaged. The density of cast charge is $\rho_{cast} = 1.598$ g/cm^3, and the corresponding absolute porosity is $m_{cast,\,\mathrm{exp}} = 0.039$.

B. Justification of the use of the charge diameter equal to 8 mm for the investigation of TNT

Since the low sensitivity of cast TNT charges and a small diameter used in experiments, some words need to be said in support of the utilized experimental setup.

Critical diameter d_{cr} for cast TNT charges is from 12.6 mm to 27.5 mm, whereas for pressed ones, it is from 2.5 mm to 5 mm.[13,32–38] If one relates the concept of the HE sensitivity to the critical diameter, wide limits of change of the sensitivity are obtained depending on the charge structure.

In the present work, the diameter of charges used is 8 mm. Charges are placed into thick copper casing. Common definition of the critical diameter is for charges without shell or with the use of fragile, low strength casing. According to the theory of Kobylkin,[38–41]

critical diameter decreases by 6 ÷ 8 times when the charge is placed into a heavy metal casing. The value of the critical diameter equal to 12.6 mm was obtained in the work[13] for a cast charge with the structure similar to one used in the present work. According to Kobylkin, this gives the critical diameter not larger than 2 mm for a charge in a thick copper casing, which is several times smaller than the diameter used in our experiments. The same is valid also for cast TNT charges with the addition of glass microspheres. All other investigated charges with different structures are made of fine-grained TNT. Their critical diameters even without shell are smaller than one used in experiment.

III. EXPERIMENTAL RESULTS FOR THE ELECTRIC PROPERTIES OF TNT

A. Influence of the charge structure and the preparation procedure on the reaction zone kinetics at the detonation of high-density TNT charges

Since the conductivity is realized along the structures formed due to the carbon condensation, it should track the details of chemical reactions at the observed relatively long reaction zone. As mentioned before, TNT is a unique material where the strong dependence of chemical peak kinetics on the charge structure is observed. As shown in the works,[42,43] the rates of chemical reactions in cast and pressed TNT differ by about the factor of 6, which should be reflected at the graph $\sigma(t)$.

Lines 1–4 of Table I show the results of the experimental investigation of high-density TNT with different charge structures. Figure 2 presents the conductivity graphs at the detonation of pressed TNT (line 1), cast TNT (2, 3), cast TNT under the action of high-intensity shock (line 4, data of the paper[27]) and liquid TNT (line 5, data of Refs. 17 and 18) The profile 5 is very short—20 ns, and it practically coincides with the initial part of the signal 1.

TABLE I. Data on the experimental investigation of TNT charges.

N	Condition	ρ, g/cm^3	D, km/s	σ_{max}, Ohm^{-1}cm^{-1}
1	Pressed	1.6	6.66	103
2	Pressed	1.6	6.81	80
3	Cast	1.6	6.43	33
4	Cast	1.6	6.43	28
5	Cast + 3% GMB	1.4	5.59	33
6	Cast + 3% GMB	1.4	5.72	28
7	Bulk density	1.1	5.15	15
8	Bulk density	1.1	5.06	15
9	Bulk density + 3% GMB	1.0	4.03	4.5
10	Bulk density + 3% GMB	1.0	4.14	4.4
11	Bulk density + 6% GMB	0.8	3.74	1.5
12	Bulk density + 6% GMB	0.9	3.69	1.7

The total density is given for charges 5, 6, and 9–12.

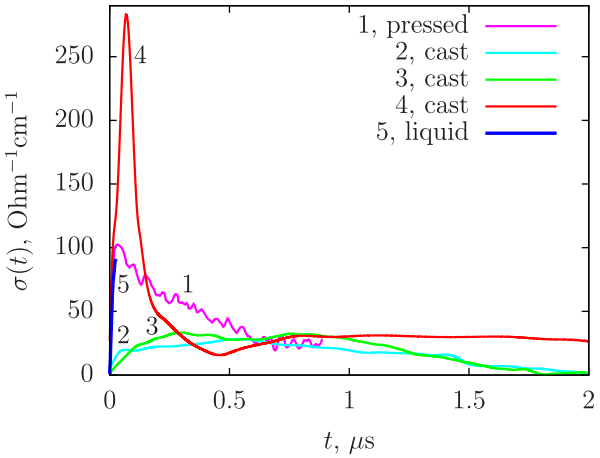

FIG. 2. Graphs of electric conductivity at the TNT detonation: 1—pressed, 2 and 3—cast, 4—cast at the high intense shock impact,[27] 5—liquid,[17,18] and parameters corresponding to the lines 1–3 (data of the present work) are given in Table I (lines 1, 3, and 4).

The maximum value of conductivity in detonating cast TNT obtained by the differential high-resolution method is confirmed by the measurements made using the integral method described in the paper.[44] The graph has the shape of an extended plateau with approximately constant value of $\sigma \approx 30$ Ohm^{-1}cm^{-1}. In pressed charge (line 1), a smooth decrease is observed after fast reach of the maximum. There is an inflexion point at $t \approx 0.6$ μs, which can be related to the end of the reaction zone at the detonation of TNT charge of small diameter. The time difference between the signal beginning and the inflexion point is close (taking into account the difference between Euler and Lagrange coordinates) to the value obtained in the work.[45] For the charge with the diameter of 120 mm, the duration of the reaction zone is 305 ns.

It is necessary to pay attention to the fact of the large difference between the maximum conductivity for cast and pressed charges: about 30 and 103 Ohm^{-1}cm^{-1}, correspondingly. For comparison, in octogen such decrease is observed for the decreasing by 30% detonation velocity.[29] For cast and pressed TNT charges, the difference of detonation velocity is less than 4%, i.e., they have close thermodynamic parameters. In the framework of the hypothesis of the determinant role of the carbon mass fraction (which in this case is obviously the same, and it does not depend on the structure), an additional explanation is necessary.

The phenomenon of the different kinetics in TNT charges prepared by different methods is well known. In the book,[33] cast and pressed TNT are considered as different materials with different parameters. Moreover, it is commonly assumed to distinguish cast TNT with different structures.[33,34,46] The critical diameters of cast charges can differ by the factor of 2 Refs. 13 and 34 (14.5 and 27 mm). In the context of the critical diameter theory of Kobylkin, where d_{cr} is inversely proportional to the rate of the chemical reaction, a pressed TNT charge with d_{cr} from 2.5 to 5 mm exceeds a cast charge several times by the rate of the chemical reaction. This is confirmed by the

results of,[42,43] where the difference of the rate of kinetics for differently prepared charges by the factor of 6 was obtained. Thus, for the high explosive with a strong dependence of the reaction zone kinetics on the charge structure, TNT, the threefold difference of the maximum conductivity is considered as a result of intensification of the reaction rate in pressed charges. At the structure level, the value of conductivity is determined by the configuration of carbon aggregates, which are formed due to the shock compression and further chemical reactions. This is in turn connected with the details of the kinetics. Hence, the sensitivity of the method of diagnostics through the electric conductivity is confirmed by the data of different authors and by essentially different investigation methods. The increase in the maximum value σ_{max} reflects more intense chemical reaction.

In curve 4, a narrow region of high values with the maximum of 280 $\mathrm{Ohm}^{-1}\,\mathrm{cm}^{-1}$ is visible. Its duration is about 100 ns. In our opinion, the presence of a peak with the magnitude three times higher than one obtained in the present work is a consequence of the shock impact on the HE. Thus, it results from an unsteady process. A long constant "tail" at $0.7 < t < 2$ μs can be explained by the high thermodynamic parameters whose decline is suppressed in the experimental setup used in Ref. 27. In addition, a non-monotony is present in the signal manifesting itself as a trough between the peak and the plateau of conductivity at $0.35 < t < 0.75$ μs. Similar feature was observed at the graphs of conductivity at the detonation of TNT in the works,[23,24] and at the graphs of conductivity in detonating hexogen, octogen and pentaerythritol tetranitrate (PETN) in Ref. 25. Figure 3 presents the simulation results of the response of the integral experimental cell for the case of a step-like conductivity distribution (line 1). When the detonation wave touches the central electrode, the whole highly conductive region gets involved in the conductivity process (in the picture, this region ends at $x \approx 1$ mm). When the electrode deepens into the detonation wave by $x \approx 1$ mm, the "tail" region with lower conductivity also switches on. This produces a characteristic curve with a trough similar to one observed at curve 4 of Fig. 2. Note that the integrals of signals 4 and 1 up to the time $t \approx 0.6$ μs coincide, which confirmed the correctness of our interpretation of data.

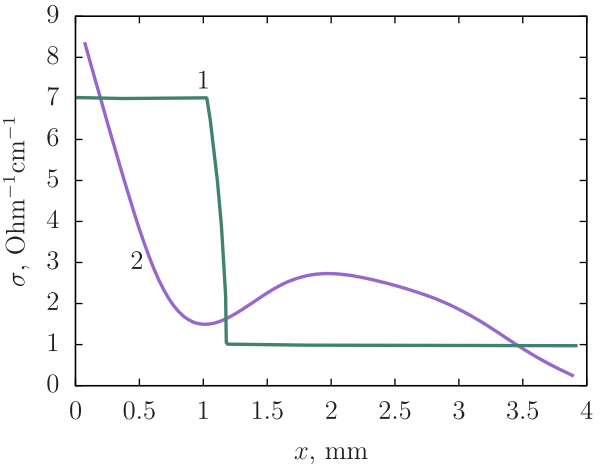

FIG. 3. Result of simulation of the response of the experimental cell (line 2) for the given distribution of the electric conductivity (line 1), work,[47] using integral measurement setup.

It is worth special mentioning that in the interval of $0.6 < t < 0.9$ μs, the conductivity graphs for cast and pressed TNT are nearly identical, as well as the profiles from the work.[27] This is a good cross-confirmation of results for the stage when the information about the initiation method and the charge structure stops to influence the measurement results.

B. Investigation results for TNT with added GMB

The sensitivity of high explosives can be changed by the addition of sensitizer. For low-sensitive industrial emulsion HE, GMB are commonly used as a sensitizer.[48,49] Without them, the chemical reaction does not develop even under shock loading of 37 GPa.[50]

Since the sensitivity of cast TNT charges is rather low,[35,37,38] an idea arises to check the influence of the addition of a sensitizer. For this purpose, it was proposed to use hollow GMB. GMB have low strength, and they are easily crushed in a detonation wave. The presence of microspheres lead to the increase in the number of pores, which in the model of hot spots are the initiation places for chemical reactions. Therefore, it was expected that this would lead to the intensifying of detonation kinetics. Production of cast charges with GMB is complicated since they float, and it is hard to control uniformity of casting. Nevertheless, the casting is made by small portions expecting the formation of a layered structure of HE and HE with microspheres. We thought that the intensified reaction in mixed layers would reveal itself at the conductivity graphs.

Figure 4, **top** shows the experimental effect of the addition of microspheres. Lines 1 and 2 are the conductivity graphs for cast charges, and lines 3 and 4 correspond to cast charges with added 3% of mass of microspheres. In addition to the absence of an explicit influence on the sensitivity and the intensifying of reaction, microspheres reveal themselves by the decrease in the detonation velocity, which is equivalent to the addition of inert material with corresponding decrease in the density of active substance. The layered alignment of GMB and TNT is visible in the graph 3: there are high-density layers with increased conductivity alongside the region containing microspheres. The maximum of conductivity at the graphs 3 and 4 is close to one at graphs 1 and 2 for pure TNT. These results show that the mechanism of the development of chemical reaction may be significantly different in emulsion HE and TNT.

Experiments are carried out with bulk density TNT and the different mass fractions of GMB added. The results are shown in Fig. 4, **bottom**. The largest σ_{max} is observed in pure HE. Addition of GMB results in the monotonous decrease in the values. At 10% of microspheres, detonation does not develop. Since GMB do not work as a sensitizer for TNT, as shown above, their role comes down to the partial occupation of the volume leading to the decrease in the amount of reacting HE, the same as in the case of cast charges.

Estimate of the concentration of GMB in cast TNT is 1.5×10^6 cm^{-3} (the procedure described in the work[50] is used for calculations). The concentration of intrinsic inhomogeneities (holes) was obtained in Ref. 13, and it is about 1.43×10^9 cm^{-3} for cast charges. Thus, in a cast TNT charge with 3% of GMB added, the concentration of own inhomogeneities is by three orders of magnitude higher. This explains the absence of the sensitizing effect from the addition of microspheres. Based on this fact, it is possible to conclude that the reaction in TNT charges develops at the own inhomogeneities, which are more abundant in pressed TNT.

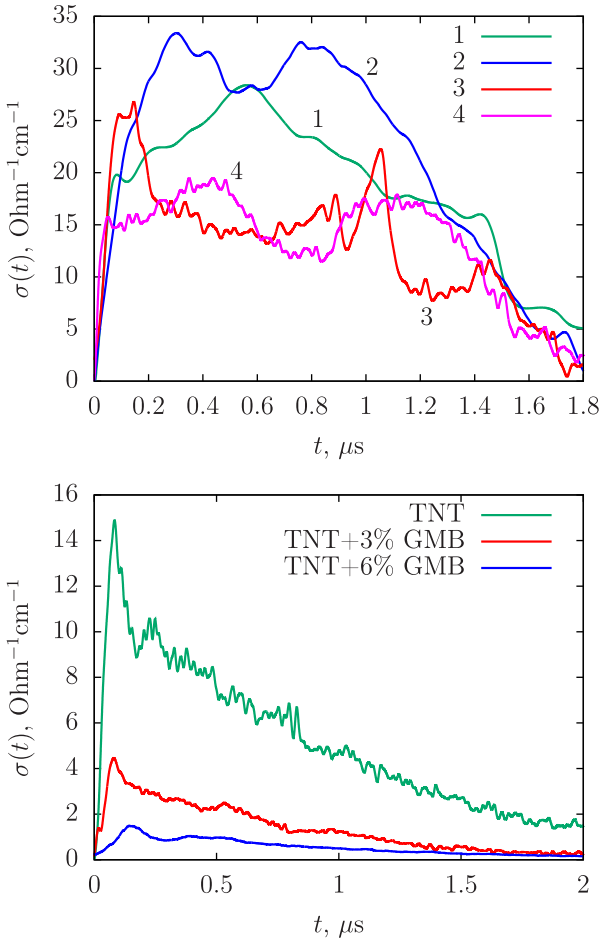

FIG. 4. Influence of microspheres on the electric conductivity. **Top**: conductivity graphs for cast TNT of the density of $\rho = 1.6$ g/cm^3 (lines 1 and 2) and cast TNT with 3% of GMB added of density $\rho = 1.39$ g/cm^3 (lines 3 and 4). **Bottom**: conductivity graphs for TNT of bulk density ($\rho_{TNT} = 1.09$ g/cm^3), with 3% of GMB added ($\rho_{TNT} = 0.97$ g/cm^3) and with 6% of GMB added $\rho_{TNT} = 0.78$ g/cm^3.

C. Influence of the addition of water to bulk density TNT charges

Before the systematic investigations of the electric conductivity, it was commonly assumed that the conductivity at the detonation is related to the presence of water in all HEs except TNT. According to the data of Ref. 51, the water content in detonation products of hexogen, octogen, PETN, and TNT is about 20%, which is formally enough to provide the observed conductivity. With the absence of investigation results on hydrogen-less HEs (such investigations are presented in Ref. 52) this point of view can explain satisfactorily the conductivity observed in bulk density charges.[20] According to Refs. 53 and 54, the dissociation of water is noticeable at detonation pressures. Thus, in the framework of the ionic conductivity caused by the dissociation of water, the addition of water to HE charges should lead to the increase in conductivity.

Figure 5 presents the results for the bulk density TNT with and without water. The experimental data are shown in Table II.

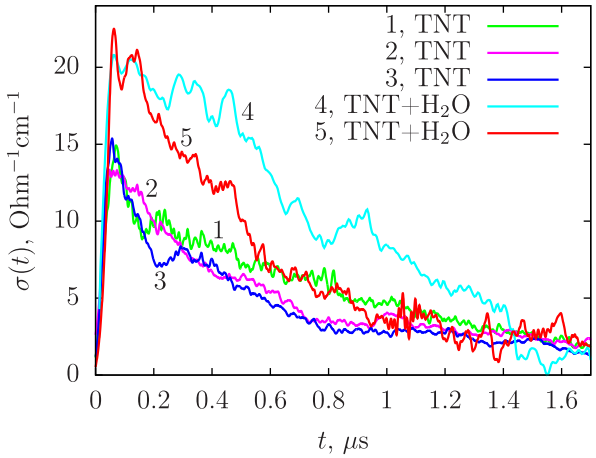

FIG. 5. Conductivity graphs for bulk density TNT (lines 1–3), for bulk density TNT with added water (lines 4 and 5). Charge properties correspond to ones listed in Table II.

The contrast of the high-conductivity region is lower than that in HEs with average oxygen balance. The graph is smooth, without prominent features and kinks. It is impossible to pick out a point, which can be related to the end of the reaction zone. The conductivity do not decrease to zero even after 1.6 μs; instead, it keeps rather high value of 3 Ohm^{-1}cm^{-1}. The graphs are reproduced well for similar densities.

At the same graph, the results for a detonating mixture of TNT and water are presented. In the experiments, TNT and water are mixed in such way that the volume fraction of water is nearly 30%. This gives the fraction of HE approximately the same as in bulk density charges, but pores are filled with water. Thus, the amount of reactive material in all experiments shown in the graph is nearly the same. Nevertheless, a significant increase in the maximum conductivity is observed, from 15 Ohm^{-1}cm^{-1} for pure TNT to 21 Ohm^{-1}cm^{-1} for mixture. Since the electric conductivity at the detonation was earlier explained by water, it is tempting to relate this increase in σ to the additive. For bulk density TNT with parameters listed in lines 1–3 of Table II, the pressure in the Chapman–Jouguet point is about 6 GPa, and the corresponding value of the water conductivity is ≈ 0.0012 Ohm^{-1}cm^{-1}.[55] Estimates give the pressure of the mixture about 12 GPa. The conductivity of water at such pressure is ≈ 0.21 Ohm^{-1}cm^{-1}. Thus, in the experiment, a value of electrical conductivity was obtained that exceeds the electrical conductivity of water by an order of magnitude; hence, the dissociation of water cannot explain the observed effect.

IV. DISCUSSION

The results of experimental studies of TNT charges with different initial conditions must be discussed within the framework of the electrical conductivity model, in which the conductivity is ensured by contacting carbon particles that form percolative clusters and tracks the evolution of the conducting form of carbon. The next paragraph is devoted to the electrical conductivity model.

TABLE II. Data on the experimental investigation of bulk density TNT charges (lines 1–3) and bulk density TNT charges with water added (lines 4 and 5; total density is given).

N	composition	ρ, g/cm^3	D, km/s	σ_{max}, Ohm^{-1}cm^{-1}
1	TNT	1.09	5.06	15
2	TNT	1.15	4.95	14.2
3	TNT	1.1	4.63	15.1
4	TNT + H_2O	$\approx$ 1.43	5.90	20.8
5	TNT + H_2O	$\approx$ 1.44	5.23	22.5

A. On the nature of the electric conductivity at the detonation of condensed HEs of the CHNO composition

The hypothesis of the contact conductivity along carbon aggregates was for the first time proposed by Hayes in 1965 in the work.[17] In this work, the very high conductivity value of 100 Ohm^{-1} cm^{-1} was measured at the detonation of liquid TNT. The author mentions the connection between the conductivity value and carbon condensed behind the chemical reaction zone. In the work of Gilev *et al.*,[27] the high value of electric conductivity for TNT was confirmed, and the assumption was made that "elongated structures with almost metallic conductivity" are present already in the region of chemical peak. The authors also remark that the conductivity mechanism in TNT is different from the one for other HEs. There are different hypotheses on the possible mechanisms of conductivity at the detonation of HEs, which include chemoionization, semiconductor conductivity under high pressure conditions, ionic mechanism including water ionization, thermal emission, and thermal ionization.[20,38,56–58] However, none of them can explain the totality of experimental data. Thus, the question of the nature of conductivity in condensed HEs at the detonation remained open for long time.

Earlier, the high-resolution method for measuring the electric conductivity was developed.[28,29] Using this method, a broad spectrum of experimental data on the electric conductivity was obtained for a series of Hes with different parameters of detonation for different initial conditions.[28,29,44,48,49,52,59–74] Based on these experimental data, a comprehensive investigation was carried out, which contains the analysis of the preserved detonation products, of the correlation between the value of conductivity and thermodynamic parameters, the composition of products in the Chapman–Jouguet point, and the elements of the original HE.[52,66] The comparative analysis shows that the zone of the chemical reaction correlates with the region of high electric conductivity, and the maximum value of conductivity is reached inside the reaction zone.[52,66] We demonstrate that the monotonous correlation of the value of conductivity is observed only with carbon, and the higher the maximum value is, the higher is the carbon content in the molecule of HE.[49,63] The inflection point at the graph $\sigma(t)$ can be associated with the Chapman–Jouguet point. This is supported by the increase in the value of σ_{CJ} with the increasing mass fraction of carbon obtained using the modified Becker-Kistiakowsky-Wilson (BKW) equation of state.[51] Investigation of preserved detonation products of carbon-rich HEs by the transmission electron microscopy revealed the presence of extended carbon structures of conductive graphite form.[72] These structures were formed in the region of von Neumann spike. They provide the contact conductivity observed in experiments.

It is shown that none of the conductivity mechanisms except the contact one can explain satisfactorily the experimental data on the electric conductivity. The correlation between the value of conductivity and the carbon content is observed, and high values can be explained only in the framework of the contact conductivity.

The model is formulated of conductivity at the detonation of solid high explosives of $C_aH_bN_cO_d$ composition. In this model, a formation of extended carbon structures starts in the detonation front, the maximum conductivity is reached at some distance behind the front, and the time to reach the maximum is of order of 10 ns in all HE except the high-density benzotrifuroxan.[52,73] The conductivity is realized through long carbon structures connecting the electrodes. Further in the reaction zone, oxidation reaction proceeds involving carbon atoms placed at the surface of carbon "nets." This leads to the thinning and partial breaking of conductive structures resulting in the decrease in conductivity. This model explains all the experimental data, and it agrees with the data of other methods.

The model of conductivity developed allows one to diagnose the kinetics of chemical reactions in the region of chemical peak at the detonation of condensed HEs.[13,70,74] This provides the possibility to investigate the reaction zone in both high-density and bulk density charges. Thus, the electric conductivity is a unique parameter for the diagnostic of the detonation process. The efficiency of our method is confirmed by the comparison with the results obtained by other approaches.

B. Influence of the density of the TNT charge on the behavior of conductivity at the detonation

With the decreasing density, the maximum value of the electric conductivity drops abruptly. Figure 6 shows the evolution of conductivity profile for TNT with the change of the charge density and structure. Corresponding parameters and lines are listed in Table I. All charges except cast one and cast with GMB added (lines 3–6) are prepared from grains identical by the structure and the size. Therefore, the decrease in the maximum value from curve 1 to curve 12 demonstrates the role of density, which is similar to the results obtained with other HEs, and the maximum value of the electric conductivity decreases with the decreasing density. The maximum value for cast TNT is lower than that for pressed one. This reflects the intensification of the chemical reaction in pressed TNT, which is a commonly known fact.

Since electrical conductivity is determined by penetrating carbon structures, as their concentration decreases with decreasing density, the structures become looser, thinner and, as a result, less conductive. This also applies to the Taylor wave region, where electrical conductivity is provided by the so-called free carbon that remains after oxidation reactions. According to the work,[51] the mass fraction of free carbon decreases with density.

The conductivity profile does not contain a narrow peak that can be associated with a reaction zone, as for other more oxygen-balanced explosives. This is due to a significant mass fraction of free carbon, which, according to the work,[51] at the CJ point during the detonation of high-density TNT is about 0.27. This is significantly higher than the mass fraction of carbon in the molecules of substances such as, for example, RDX. Therefore, the region of the chemical reaction on the

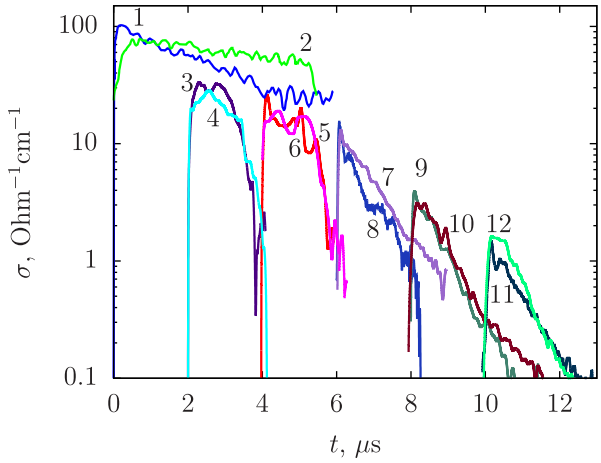

FIG. 6. Conductivity graphs at detonation of TNT with different densities and charge structures. 1 and 2—pressed charges; 3 and 4—cast charges; 5 and 6—cast charges with 3% GMB added; 7 and 8—bulk density charges of pure TNT; 9 and 10—bulk density charges with 3% GMB added; and 11 and 12—bulk density charges with 6% GMB added. Charge properties correspond to ones listed in Table I. Graphs for charges of the same structure, density, and composition are shifted along the X axis.

TNT electrical conductivity profile does not stand out clearly. However, as the density decreases, the carbon concentration drops, the electrical conductivity gradient increases, and the contrast of the region of high values on the profile increases.

C. Effect of water on the conductivity profile

The increase in the maximum value of σ_{max} for the TNT+water mixture is explained in the following. At the detonation of mixture, pressure increases due to the reaction of TNT. The detonation products are compressed compared with the same amount of the active material in the case of the detonation of a bulk density charge. The volume occupied by TNT becomes smaller, which leads to the more effective formation of penetrating carbon structures. Mixing of TNT and water in the detonation wave takes place only at the contact boundary,[44,75] i.e., HE weakly interacts with water. Thus, water is a weakly reacting medium, functional action of which comes down to the occupation of volume that was filled with the medium of the detonation wave in the case of pure TNT. Thus, the obtained value of σ_{max} corresponds to a larger effective density of TNT. This agrees fully with the increase in the conductivity at the increasing density and is also confirmed by the values of conductivity at the detonation of a cast TNT charge with GMB added (Fig. 4, **top** lines 3, 4) whose presence is equivalent to the density decrease in the energetic material. The additional argument in support of the correct interpretation of the results is the experimental investigation of the conductivity at the detonation of bulk density hexogen with water-filled pores (setup similar to the present work).[60] There, the maximum conductivity for the hexogen-water charge was the same as for pure hexogen within the limits of experimental errors. In the case of essential mixing of detonation products with water, the decrease in the conductivity value would occur compared with pure HE. Thus, the experimental investigation of the TNT charges with water added shows that there is no significant mixture of detonation products with water including the region of von Neumann spike. This confirms the conclusion of the works[44,75,76] where the mixing of two detonating materials was investigated experimentally and numerically. An increase in the electrical conductivity value for TNT+water charges is associated with an increase in the local concentration of carbon atoms.

D. Comparison of the results of the conductivity measurements with the literature data

Figure 7 presents the literature data on the investigation of the electric conductivity at the detonation of TNT and the results of the present work. The graph does not contain the results of early investigations with an understated conductivity value.[20–22] Liquid phase state and pressed charges are indicated. The conductivity for TNT charges reaches record values among all HEs investigated. Most broad range is also obtained. Totally, the results of the present work are in a satisfactory agreement with the literature data. The trend is visible of the increase in conductivity with increasing density.

E. Width of the reaction zone at the detonation of TNT charges with different structures and densities

As shown in Refs. 69 and 71, the zone of high conductivity at the detonation of HE with average oxygen balance correlates with the chemical peak. It is appropriate to compare the results on the measurement of reaction zone parameters at the detonation of TNT obtained by different methods. In Fig. 8, all the presently available literature data are shown on the reaction zone width at the detonation of TNT charges with different structures and densities. Marks 2 and 3 denote the values given in review works in order to compare them with the authors' data. In several works, the duration is shown instead of the width; hence, the width is calculated similar to Ref. 71.

Data shown in Fig. 8 demonstrate a high degree of uncertainty in the parameters of the reaction zone. The observed scatter of values is

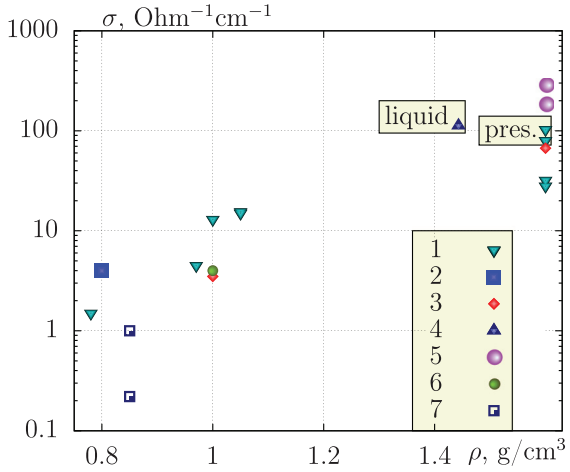

FIG. 7. Comparison of the results of the experimental investigation of conductivity at the detonation of TNT charges with different densities and structures. The mark 1 denotes the maximum conductivity data of the present work. 2—(Ref. 16), 3—(Refs. 23–25), 4—(Refs. 17 and 18), 5—(Ref. 27), 6—(Ref. 19), and 7—(Ref. 26). All charges at the density $\rho \approx 1.6$ g/cm^3 are cast except ones marked as pressed.

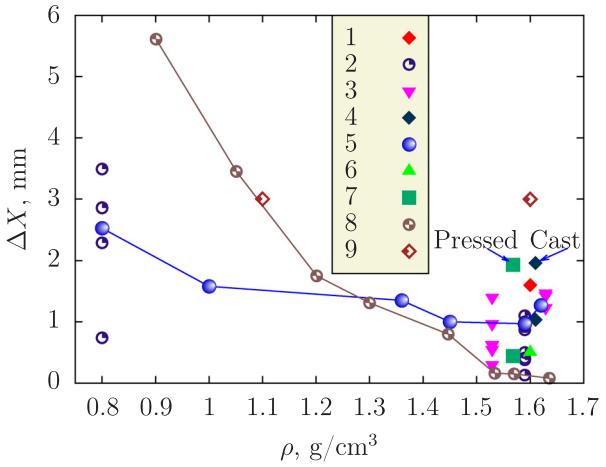

FIG. 8. Width of the reaction zone at the detonation of TNT charges with different structures and densities: 1—(Ref. 45); 2—(Ref. 77); 3—(Ref. 46); 4—(Ref. 34); 5—(Ref. 33); 6—(Ref. 27); 7—(Ref. 78); 8—(Ref. 79); and 9—present work. For density about 1.6 g/cm^3 with a close value of ΔX, the charge preparation details are shown by the arrowed captions.

an order of magnitude both for bulk density and high-density charges. As mentioned above, a common practice is to distinguish cast and pressed TNT charges of the same density. However, for the density of ≈ 1.6 g/cm^3, two points are present with the same width of the reaction zone and different methods of the charge production. This result contradicts severely to the commonly known data. It can be explained by the absence of a universal method to determine the end of the reaction zone when using a broad range of experimental approaches. In addition, as noted in Ref. 46, parameters of the reaction zone are not constant. They depend on a variety of factors defined by the geometry and the structure of a HE charge. Taking this into account, the results obtained at the investigation of electric conductivity do not contradict to the literature data.

V. CONCLUSION

The electric conductivity at the detonation of TNT charges with different structures, densities, and inert additives is investigated experimentally using the high resolution method.

Time dependence of the electric conductivity at the detonation of high-density TNT charges is determined by the charge structure. In pressed charges, the maximum conductivity of $\sigma_{max} \approx 100$ Ohm^{-1} cm^{-1} is observed reliably, whereas in cast charges, the value is three times lower. Such a large difference is connected with different kinetics, which is confirmed by the data of different authors.[41–43] For pressed charges, the profile has a smooth triangular shape without pronounced features; for cast charges, the signal is nearly step-like. The maximum value decreases with the decreasing charge density. Similar decrease is observed in other HEs, and it is explained by the decrease in the carbon concentration synchronous with the density. Addition of GMB to TNT does not lead to the intensification of chemical reaction (although such addition effectively increases the sensitivity of emulsion HEs). GMB occupy the useful volume and lead to decrease in the effective density of HE. Similar influence of the effective density decrease for the active component is obtained for the addition of GMB to the bulk density TNT charges. Filling the pores of the bulk density charge with water leads to the notable increase of the conductivity though its level remains lower than that in dense TNT. This is explained by the weak mixing of detonation products, which leads to some compression of products working similarly to the increase in the density of active component. This is confirmed by the comparison of conductivity graphs for high-density charges of pure TNT and for charges with water added. The change in electrical conductivity with increasing density, as well as with the addition of water and microspheres, is explained by a change in the carbon concentration. Comparison of the experimental data on the electric characteristics and the width of the reaction zone with the literature data show a good agreement.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Nataliya P. Satonkina: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Resources (equal); Supervision (lead); Visualization (lead); Writing – original draft (lead); Writing – review & editing (lead). **A. P. Ershov:** Conceptualization (equal); Formal analysis (equal); Investigation (equal); Methodology (equal). **D. A. Medvedev:** Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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