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Laboratory and field tests on the hydro-jet washing out of TNT from artillery shells
Laboratoryjne i poligonowe badania hydrostrumieniowego wypłukiwania TNT z pocisków artyleryjskich

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Abstract: *The article discusses issues associated with removing explosive from artillery shells, with particular focus on hydrofluidic washing out technology. A multi-well hydraulic test site and high-pressure work equipment, as well as testing methodology used in field tests, which allow washing out of explosive materials from such ordnance using a high-pressure water jet, are presented. The studies on the hydro-jet process of washing out trinitrotoluene (TNT) were carried out on high-explosive (HE) shells with calibres of 85, 100, 122 and 125 mm.*

As a result of the tests, the variability of the TNT washing out mechanism, dependent on hydro- and thermodynamic conditions of this process, which in turn are dependent mainly on the pressure of the water jet, was proven. Comparison of the results of these experiments with the results of previous studies on the washing out of a substitute material which duplicated the mechanical properties, resulted in the determination of an appropriate factor correcting the potential effectiveness of such a process, which allows conducting safe simulation tests under laboratory conditions. In turn, evaluation of the morphology and geometrical structure of washed out TNT, as well as its thermal stability and detonation velocity made it possible to suggest possible applications of the washed out explosive material, especially as a component of mining explosive materials.

Streszczenie: *W artykule omówiono zagadnienia usuwania materiałów wybuchowych z pocisków artyleryjskich, koncentrując się zwłaszcza na ich wypłukiwaniu hydrostrumieniowym. Zaprezentowano w nim wielogniazdowe stanowisko badawcze o napędzie hydraulicznym i wysokociśnieniowy osprzęt roboczy oraz metodykę badań stosowaną w warunkach poligonowych, które umożliwiają wypłukiwanie materiałów wybuchowych (MW) z takich pocisków przy zastosowaniu wysokociśnieniowej strugi wodnej. Badania procesu hydrostrumieniowego wypłukiwania trotylu przeprowadzono dla pocisków odłamkowo-burzących o kalibrach 85, 100, 122 i 125 mm.*

W wyniku badań stwierdzono zmienność mechanizmu wypłukiwania TNT, uwarunkowaną hydro- i termodynamicznymi warunkami tego procesu, zależnymi głównie od ciśnienia strugi wodnej. Porównanie wyników tych eksperymentów z wynikami wcześniejszych badań nad wypłukiwaniem materiału zastępczego, imitującego właściwości mechaniczne MW, pozwoliło na określenie odpowiedniego *współczynnika korygującego potencjalną efektywność takiego procesu, co umożliwia przeprowadzanie bezpiecznych badań symulacyjnych w warunkach laboratoryjnych. Z kolei przeprowadzenie badań morfologii i struktury geometrycznej wypłukiwanego TNT, stabilności termicznej i prędkości detonacji umożliwiło zaproponowanie kierunków wykorzystania wypłukanego MW, szczególnie jako składnika górniczych MW.*

Keywords: *explosives, artillery ammunition, high-pressure water jet*
Słowa kluczowe: *materiały wybuchowe, amunicja artyleryjska, wysokociśnieniowa struga wodna*

1. Introduction

The rational management of various military artillery supplies in Poland is a serious problem requiring, *e.g.* the disposal of redundant artillery ammunition, and in particular the neutralisation of explosives [1-5]. The most commonly used methods for removing explosive materials from artillery ammunition are firing, mechanical extraction and smelting with hot water or superheated steam [6]. The latest methods for removing explosive materials from artillery and rocket ammunition include washing and washing out using a high-pressure water jet [1-5, 7-15]. Rarely used for this purpose is water-ice stream [16], water-abrasive stream [17] or cryogenic stream [18, 19]. These are effective methods that do not require special safety conditions [20, 21]; therefore, they have been utilised in the USA for almost twenty years [14, 22-24]. Similar solutions were also used in several European countries, such as: Russia [16], Germany, the Netherlands, Sweden and the Czech Republic [25]. Furthermore, previous results of our research [1-5, 7-12], carried out with the use of a substitute explosive, have become the basis for an adequate method for washing out explosives using a high-pressure water jet. The issue of recycling of such materials, largely solved by their application in the mining industry, is of a crucial importance [26-28]. This article contains the results of research on the washing out of TNT from artillery shells using a high-pressure water jet. The studies were conducted utilising technology discovered at the Institute of Unconventional Hydrostatic Technologies of the Koszalin University of Technology (pl. *Instytut Niekonwencjonalnych Technologii Hydrostrumieniowych Politechniki Koszalińskiej*), the experimental verification of which was carried out under field conditions at the Military Institute of Armament Technology (pl. *Wojskowy Instytut Technicznego Uzbrojenia,* WITU).

2. Research site and methodology

To ensure the a efficiency of explosive material removal, a multi-socket device (Fig. 1) with a modular structure was developed. Currently, this design allows for simultaneous removal of the explosive materials from four shells; however, ultimately they can be easily enlarged to 64 sockets. Its individual sockets are rotated by a chain gear driven by a hydraulic motor equipped with a planetary reduction gear.


(a) (b)

Figure 1. Details of the device used for washing out explosive materials: (a) general view of the 125 mm bullet inserted into the working socket; (b) four-socket module working table

For the field tests, the device was adapted for the use of a single socket by equipping it with working heads with two twisted nozzles or a single water nozzle. The central direction of each water nozzle adjustment is the projectile axis. The nozzle makes quasi-radial movements in relation to the projectile axis without exceeding the igniter opening. Such movements are ensured by an appropriate crank mechanism driven by the other adjacent working sockets of this device. The type and characteristics of water nozzles used to wash out TNT from shells were selected according to the latest research results [8, 9, 29].

Hydro-jet eroding of high explosives (HE) takes place inside the shell, into which a high-pressure water jet flows through the hole of the unscrewed igniter. The washed output flows out continuously through the same hole, which imposes the necessity for effective fragmentation into quite small pieces. A general view of the test stand utilised for washing out explosives from artillery shells using a high-pressure water jet at the WITU training ground, is shown in Fig. 2.

(a) (b)

Figure 2. General view of the universal test stand: (a) location of the individual components; (b) process of washing out TNT from a 125 mm shell

The stand is supplied with a high-pressure water jet using a suitably instrumented hydraulic monitor (Fig. 3), based on Hammelmann's pump type HDP 164 ($p_{\max}$ = 300 MPa, $Q_{\max}$ = 0.5 dm^3·s^{-1}, P = 175 HP). In the case of using modules with a larger number of working sockets, a hydraulic monitor with a higher water capacity can be used, *e.g.* HDP 483 type ($p_{\max}$ = 150 MPa, $Q_{\max}$ = 2.6 dm^3·s^{-1}, P = 750 HP).

Figure 3. Hammelmann's high pressure hydraulic monitor HDP 164 (p_{maks} = 300 MPa, Q_{maks}= 0.5 dm^3·s^{-1})

General conditions used for the removal process of HE from artillery ammunition carried out in the field tests, are presented in Table 1.

Table 1. Conditions used for washing out HE from high-explosive artillery shells of various calibers and typical quantities tested

Input quantities	The quantities tested
- water pressure p = (150-270) MPa	- time of HE washing out, Mg
- nozzle diameter d = (0.7-1.0) mm	- HE washing out efficiency, Qt
- working length of the water jet Lo = (50-525) mm	- process effectiveness, Ew
- rotational speed of the shells n = (5-20) min^{-1}	- granulation of washed out HE, Gf
- caliber of the shells k = (85, 100, 122, 125) mm	- quality of the surface of the HE granulate, Qs

3. TNT washing out mechanism

To investigate the mechanism of hydrodynamic TNT washing out from shells, endoscopic analysis of their interior was performed, which was carried out at various stages of the HE eroding process. This type of research allows for the documentation of individual stages of detaching and removing TNT from shells. An outline illustrating these kinds of processes, occurring under several selected test conditions, is presented by the sets of photographs shown in the figures below.

The typical methods for TNT hydro-jet eroding at relatively low pressures are illustrated by the typical photographs presented in Fig. 4. Based on the analysis of such images, it was found that the dynamic pressure of the water jet at a relatively low pressure value (150 MPa) usually causes decoherent chipping of larger TNT particles (Fig. 4b). In the analysed example, a double water jet using a head with two nozzles, was utilised. Its job is to facilitate detachment of TNT from the shells (Figs. 4c and 4d), which usually increases the efficiency of washing out HE from larger calibre shells.

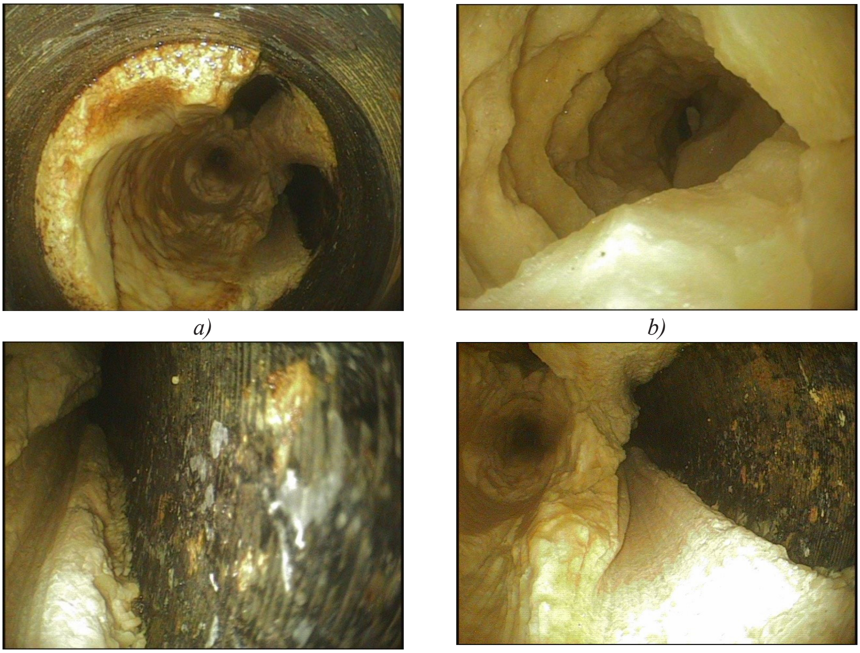
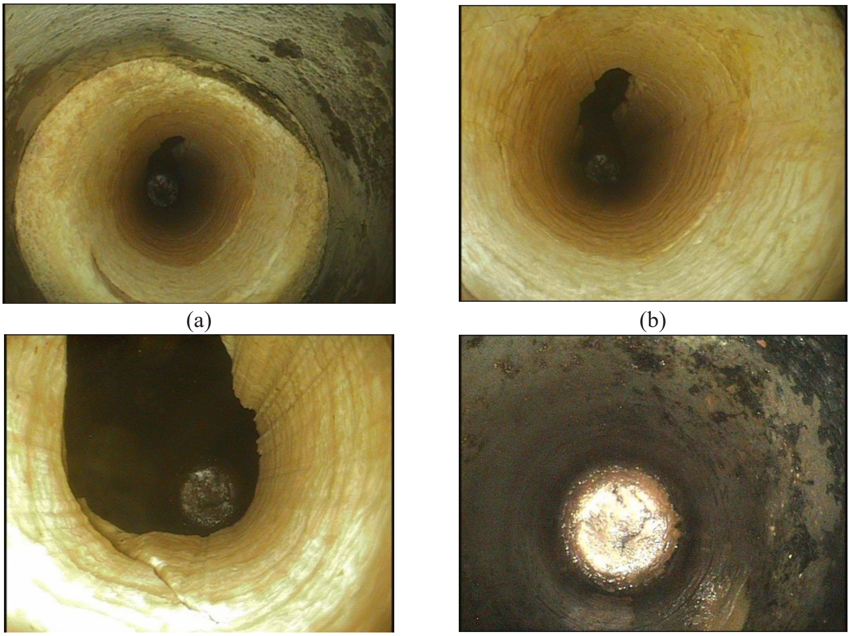

a) b)
c) d)

Figure 4. Examples of TNT eroding from a 125 mm high-explosive shell using a high-pressure water jet (p = 150 MPa) produced in a two-nozzle head (2 × 0.7 mm): (a) general view of the erosion area; (b) decoherent eroding of coarse particles of TNT along hollow channels; (c) traces of longitudinal washing using a water jet; (d) detachment of TNT from the bullet shells

A high-pressure water jet produced using a single water nozzle can also be successfully utilised for washing out TNT from an artillery shell of a smaller caliber. Details of the TNT eroding process are illustrated using endoscopic images, shown in Fig. 5.

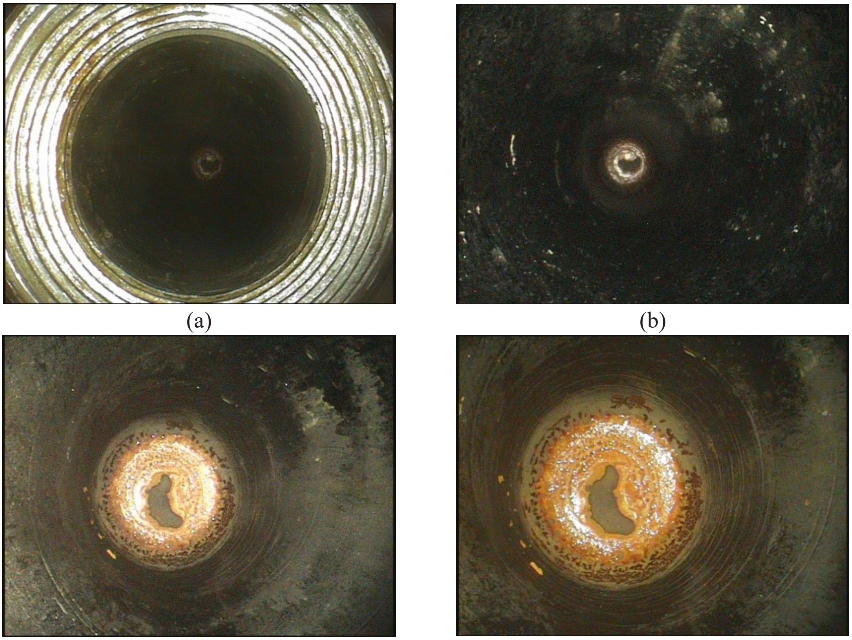


(a) (b)

(c) (d)

Figure 5. Exemplary phases of the TNT hydro-jet washing out process from a 85 mm high-explosive shell (p = 200 MPa, water nozzle Φ 1.0 mm): (a) washing out traces by the ignition hole; (b) traces of washing out deep within the shell; (c) the detail of washing out of the bottom TNT layers with visible cracks; (d) view of the washed out bottom of the bullet shells

The results of the research show that following erosion of the central hole in TNT, the high-pressure water jet flows radially at the bottom of the shell. In such conditions, hydrodynamic washing out of the bottom TNT layers occurs, and then the wider ones, resulting in crumbling into relatively large pieces. It is observed that the edges of these crumbled pieces are usually clear and sharp. This assists the process of hydrodynamic blurring of more distant TNT layers, leading to clearing of the entire shell. The effectiveness of washing out TNT from an artillery shell (calibre 85 mm) utilising this method, using a single water jet at a pressure of 200 MPa, is illustrated by endoscopic photographs shown in Fig. 6.



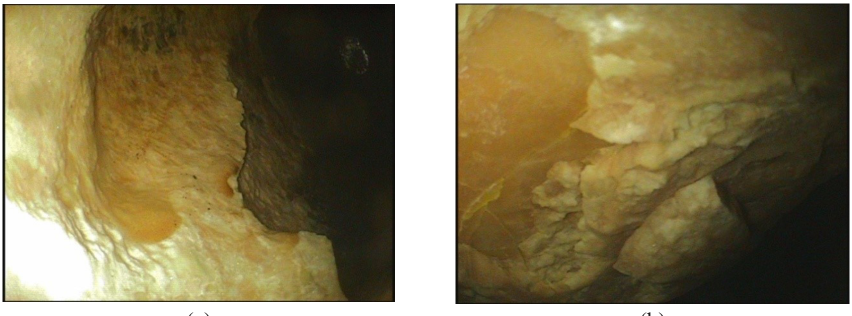
(a) (b)

(c) (d)

Figure 6. View of the inside of an 85 mm high-explosive shell following high-pressure TNT washing out (p = 200 MPa, water nozzle Φ 1.0 mm): (a) thread in the ignition hole; (b), (c) middle parts of the shell; (d) bottom part of the shell

In contrast, the occurance of specific phenomena during TNT washing out at a relatively high pressure (over 250 MPa), causes changes in the TNT removal mechanism described above. Typical examples of these types of phenomena are shown in Fig. 7.

The impact of the high-pressure water jet results in the creation of a relatively dense crack network in the surface layers of TNT (Figs. 7a and 7b) leading to the removal of fine-grained particles, which ensures the formation of surfaces generally characterised by significant smoothness (Fig. 7c). Moreover, relatively fast erosion of the central hole, down to the bottom of the shell, occurs frequently in HE. The energy of the hydrodynamic influence of the high-pressure water jet results in localised heating of the shell, causing melting of adjacent TNT layers. Due to the influence of dynamic displacements inside the shell, the particles crushed out from these layers permanently adhere to colder surfaces, especially in places with a developed geometric structure (Fig. 7d).

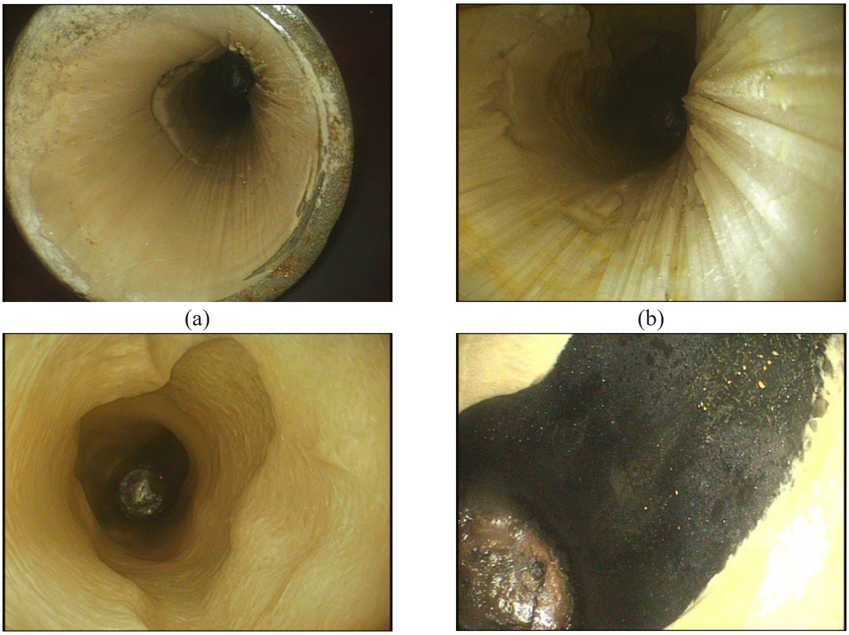


(a) (b)

(c) (d)

Figure 7. Typical examples of TNT erosion in a 100 mm high-explosive shell resulting from the influence of a high pressure ($p = 265$ MPa) water jet produced using a nozzle with a diameter of $\Phi = 0.9$ mm: (a) traces of TNT washing out and cracks; (b) cracking and peeling of the surface layer; (c) round leaches and smooth TNT surfaces; (d) melted TNT labels adhered to the thread in the igniter hole

The analogical character of the described phenomena occurs during the erosion and removal of TNT from a 122 mm shell, as illustrated by Fig. 8.



(a) (b)

(c) (d)

Figure 8. Examples of phases of the hydro-jetting process for washing out TNT from a 122 mm high-explosive shell ($p = 260$ MPa, water nozzle $\Phi = 0.9$ mm): (a) traces of washing out at the shell opening; (b) clearer traces of washing out deep within the shell; (c) relatively systematic eroding of the central hole; (d) washing out the bottom TNT layers, which makes the undercoat visible in the form of a bituminous varnish

The use of a water jet with a pressure above 250 MPa usually causes the appearance of straight washing out traces which, among other things, intensifies the TNT erosion. Furthermore, heating the bottom of the shell using the energy from the high-pressure water jet results in localised melting of the adjacent TNT layers.

All of this implies that during dynamic movements, they stick to all roughness and fill hollows, *etc*. This is evident in the form of a significant smoothing of the washed out surfaces. However, what is worse is that it contributes to the sticking of TNT in places with a developed structure, *e.g.* the thread of the igniter opening.

4. Efficiency of the HE washing out process

Increasing the pressure of the water jet and its flow, usually results in intensification of HE erosion. These basic correlations were also verified during the field tests. However, during these initial experiments, a particularly high level of safety had to be maintained. Therefore, the simplification of the kinematics of the slider-crank mechanism used to move the water nozzle was essential. As a result, the elimination of the angular movements of the nozzle in a vertical plane was needed and the preferred water jet spraying method was omitted.

Despite the occurrence of this major issue under certain conditions, satisfactory results were obtained even in the first experimental trials. This particularly applied to the small-caliber shells, where a nearly stationary, since it was only parallel, water jet washed out TNT from the shell to a satisfactory extent. Although the efficiency of these operations is reduced when compared with the washing out of the substitute material [8, 10, 11], based on the described tests, the concept of an entirely safe procedure for the HE removal has been confirmed. Conducting just these initial experiments demonstrated a safe and effective method for washing out TNT from practically any standard artillery shell. Based on fully successful tests only, it should be pointed out that the efficiency of TNT washing out amounts to 2.69-3.53 $cm^3 \cdot s^{-1}$.

To assess the effectiveness, the efficiency coefficient for this type of process was applied, which can be determined according to the formula:

$$\eta = \frac{Q_2}{Q_1} = \frac{t_1}{t_2} \tag{1}$$

where: Q_1 and Q_2 are the washing out efficiency coefficients of the HE substitute and authentic TNT, respectively, while t_1 and t_2 are the respective durations of these operations.

The determined efficiency coefficient values for this type of process lie within the range of 0.42-0.48. This shows that there is still a lot to be achieved in terms of improving the efficiency of TNT washing out from artillery shells. Therefore, optimisation of TNT washing out using a high-pressure water jet creates an opportunity to at least double the currently achieved efficiency.

It is an important requirement for the effective eroding of TNT located inside a slim shell into which a high-pressure water jet is injected through the igniter hole. This solution quite seriously impedes the outflow of larger pieces of the washed out HE, which must be fragmented first. All of this causes a drop in the effectiveness of the TNT washing out process.

However, based on these initial findings, it may be concluded that the method of hydro-jetting considered here is a competitor to other approaches used so far. Moreover, it is quite feasible to increase its efficiency by approximately two-fold by optimising the parameters and conditions of the original method. Considering the above, it may be concluded that the method for washing out TNT from shells involving a high-pressure water jet, developed at the Institute of Unconventional Hydrojetting Technologies of the University of Technology in Koszalin, is interesting with economical potential.

5. Formation of washed out TNT particles

The tests conducted on washing out HE from high-explosive artillery shells by hydro-jetting have shown the presence of diverse form and structure in the washed out TNT (Fig. 9). Depending on the hydrodynamic parameters of the jet, the washed out material appeared predominantly in the following three forms: a low molecular weight powder forming a porous “foam” remaining on the surface of the post-process water, "semolina" in the form of the particles with a size of 8-15 mm (max. 25 mm), as well as melted TNT mass.

(a) (b) (c) (d)

Figure 9. Differentiation in the structure of the TNT particles washed out using a high-pressure water jet: (a) mixture of granules from the finest particles (dried "foam") and crumbs of "semolina" stuck together; (b) dry grains of "semolina"; (c) the finest particles, from dried "foam", stuck together; (d) particles formed from melted TNT

The washed out TNT, in the form of a very finely fragmented powder, occurs mainly when using a water jet at the lowest pressures (*e.g.* in the range of 150 MPa) and a low water flow resulting from the use of nozzles with smaller diameters (*e.g.* 0.7 mm). The granularity of the TNT particles formed under such conditions falls within the range of 0.2-1.0 mm. Consequently, it results in the formation of a porous foam-like suspension, which stays on the surface of the post-processed water (Fig. 10a). In order to retrieve the particles, the water has to be filtered (Fig. 10b). As a result, a wet mush is obtained (Fig. 10c), which after drying, creates clumps that are characterised by relatively significant porosity (Fig. 10d).

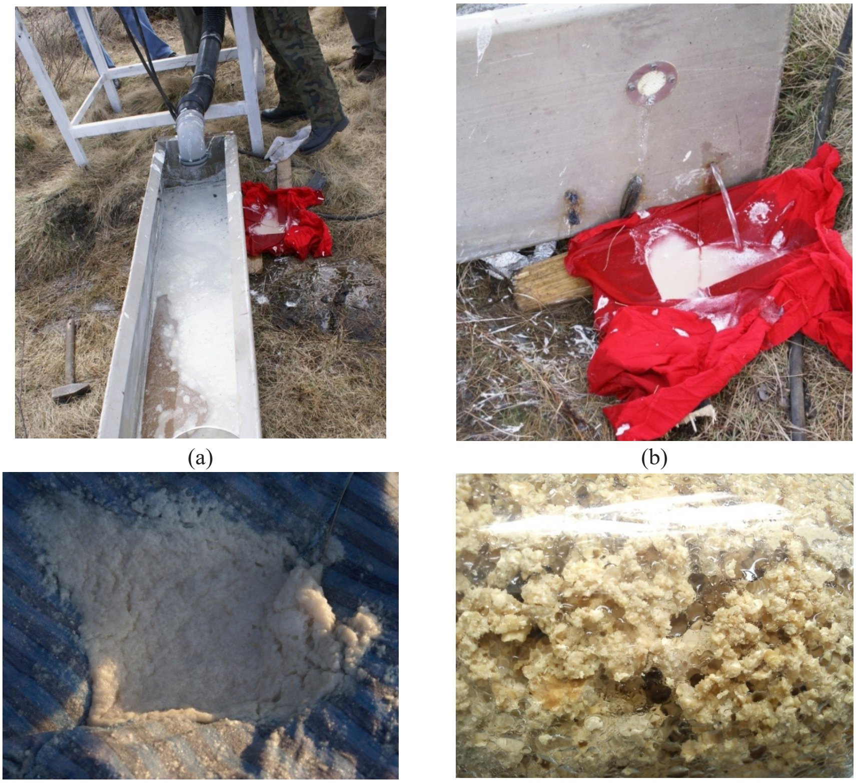

(a) (b)
(c) (d)

Figure 10. The recovery of the finest TNT particles washed out using a high-pressure water jet: (a) suspension of the particles remaining on the surface of the post-processed water as a foam; (b) straining the water; (c) wet mush of drained particles; (d) dried clumping of such particles with a significant porosity

However, it is more common for TNT particles washed out from shells using a high-pressure water jet to be in the form of "semolina" (Fig. 11), usually with a size in the range of 5-15 mm, and sometimes even up to 25 mm. A similar form of such particles occurs practically in all of the hydrodynamic conditions applied here.

Figure 11. A typical granulate of the washed out TNT particles is in the form of “semolina”

In line with the previous analyses, it may be noted that a partial melting of TNT occurs during the use of a water jet at the highest pressures (above 250 MPa). This is caused by a relatively fast erosion of TNT down to the bottom of the shell. Subsequently, the energy of the hydrodynamic influence of the high-pressure water jet results in localised heating of the projectile shell. However, heating of the shell results in the melting of adjacent TNT layers (Fig. 12a), which undergo dynamic movement and are able to permanently stick to various surfaces, solidifying particularly in the cooler areas of the shell, characterised by a developed geometric structure (Fig. 12b).

(a) (b)

Figure 12. Collected particles of molten TNT: (a) formed during washing out with a water jet at a pressure of 260 MPa and its labels; (b) 100 mm shells remaining in the furrows of the thread in the igniter hole

The abovementioned issues greatly deepened the understanding of the mechanism which determines the efficiency of hydrodynamic washing out of TNT from typical artillery shells and enabled the development of its preliminary description.

Conducting morphology tests on the widely varied surface of the washed out particles is, therefore, crucial. Most often, such particles take the form of a granulate, referred to as “semolina”, with a particle size of #(5M5) mm (max. # 25 mm). Their surface is usually quite regular and traces of the water jet influence appear only sporadically. The nature of such traces is illustrated in the sample SEM images shown in Fig. 13.

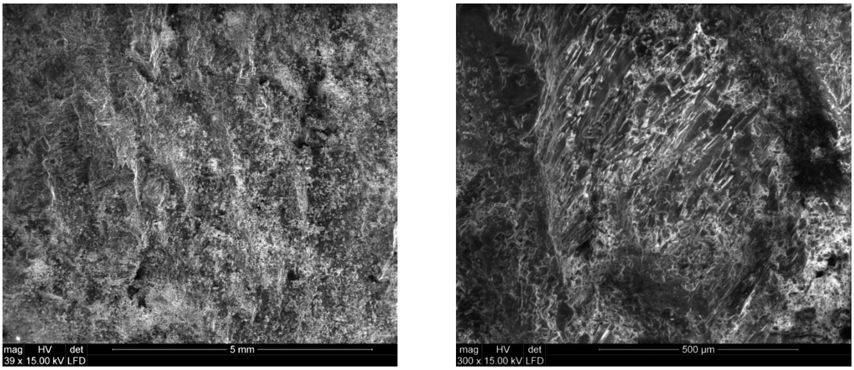


Figure 13. Sample SEM images showing the morphology of the “semolina” type TNT particle surface, washed out using a high-pressure water jet

In terms of optical perception, however, stereometry of high-pressure water jet traces on the surface of the particles is emphasised more clearly in the geometric surface structure images. They take the form of more developed scratches (Fig. 14). More importantly, however, the analysis of such geometric surface structures enables quantifying their morphology according to the following numerical indicators, which are useful in practice:

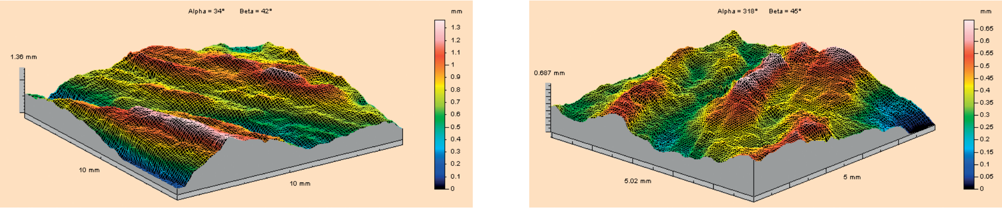
– the maximum morphology index is described using the formula:

$$W_{maks} = \frac{h_{maks}}{\sqrt{ab}} \tag{2}$$

– the average morphology index is, in turn, determined by a relation which is more difficult to implement physically:

$$W_m = \frac{\Sigma h_i}{\sqrt{ab}} \tag{3}$$

The following factors in the formulae (2) and (3): h_{maks} and h_{i} denote the maximum and the unit heights of the analysed surface inequality, respectively: $a \times b$.



(a) (b)

Figure 14. Sample TalyScans of the geometric surface structure of “semolina” type TNT particles, washed out with a high-pressure water jet

Despite the apparent optical difference of both surfaces presented in Fig. 14, the morphology of their geometric surface structures is identical. This is evidenced by almost identical values of the W_{maks} index, which is equal to 0.136 for the geometric surface structure shown in Fig. 14a, whereas in the case of that presented in Fig. 14b, it equals 0.137.

A significant part of the TNT is washed out in the form of a fine-particle powder, which clumps together and forms a porous "foam", which remains on the surface of the post-process water. After drying, such "foam" retains its porous structure, which is also reflected on its surface, an example of which is presented in Fig. 15.

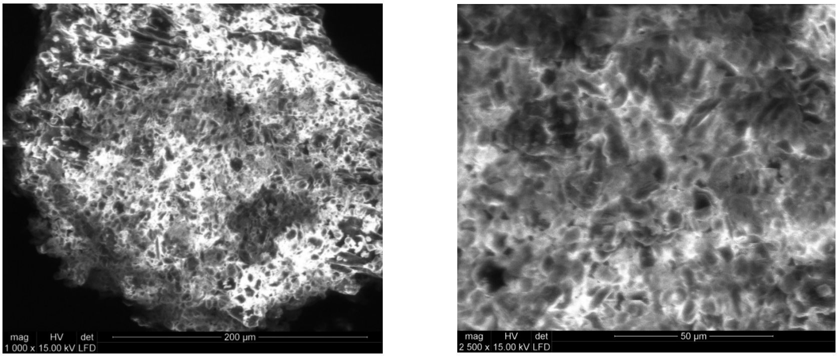


Figure 15. Sample SEM images of the surface of the most fine-grained TNT particles washed out using a high-pressure water jet, which form a porous "foam" floating on the subprocess water

The relatively irregular surface structure is also a characteristic feature of the TNT particles, which partly melted during washing out. The condition of the surface can be observed in the scanning images shown in Fig. 16. Irregularities of surface structure can be seen both at the macroscale (Fig. 16a), as well as at the microscale (Fig. 16b), which clearly shows the growth of the newly formed structures.

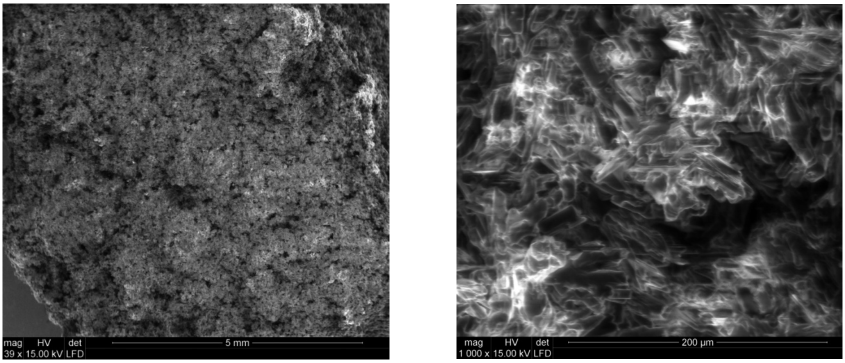
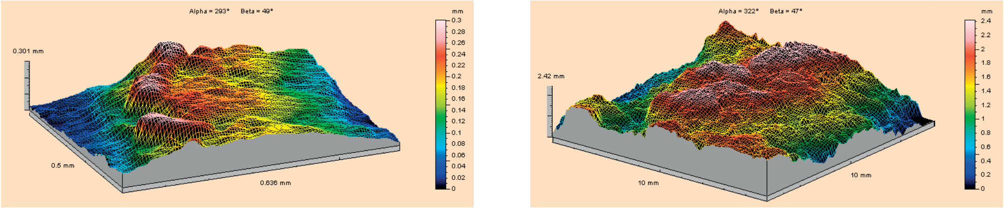


Figure 16. Sample SEM images of the surface of a partially melted TNT particle during washing out with a water jet at a pressure of 260 MPa

Quantitative information on the morphology of various forms of washed out TNT particles can be obtained from the TalyMap images, which are shown in Fig. 17.



(a) (b)

Figure 17. Sample TalyScans of morphology of geometric surface structure of TNT particles washed out with a high-pressure water jet: (a) the most fine-grained, which form a porous "foam"; (b) partially melted during washing out

Such images reflect the nature of the surface of TNT particles washed out from missiles, and at the same time show the quantitative diversity of indicators of the obtained geometric surface structure topography. Values of the maximum index W_{maks} of the geometric surface structure morphology (Fig. 17a), formed from the most fine-grained TNT particles, amount to 0.534. This particularly highly developed surface morphology results from the high porosity of this dried "foam", which forms as a conglomerate of the most fine-grained TNT particles.

In comparison with the abovementioned value, the numerical value of the maximum index W_{maks} of the morphology for such partially molten TNT (Fig. 17b) is not particularly high. This occurs despite the fact that in this case the W_{maks} index equals 0.242, which mainly results from the relatively large irregularity of the surface, previously presented in the SEM images (Fig. 16); however, it is equal to merely 45% of the characterising value of TNT in the form of a dried "foam".

6. Properties of washed out TNT

TNT obtained from hydrojetting must be subjected to a utilisation process. How this is done depends on the properties of the recovered HE. This was one of the reasons for conducting tests on thermal resistance and detonation velocity.

Differential scanning calorimetry (DSC) was used to determine the changes taking place in the explosive. This consisted of measuring and recording thermal transitions of all chemical changes and phase transitions which occur in the sample during its heating from room temperature to the temperature of decomposition. The results of the DSC differential analysis for one of the samples are presented in Fig. 18 and in Table 2. Very similar results were obtained for all of the samples. The results obtained from the experiments show that at the microscale, TNT is characterised by thermal resistance, which is typical of fresh TNT.

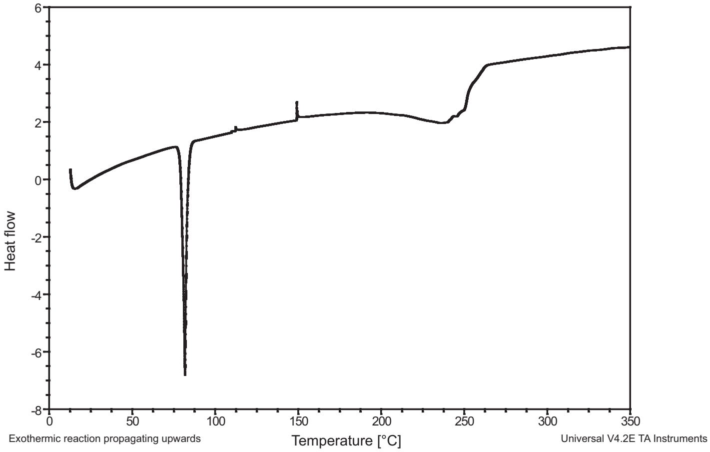


Figure 18. DSC curve of one of the washed out TNT samples

Table 2. Values of characteristic temperatures and heat of transition of the TNT sample obtained using DSC

Parameter	Transition I	Transition II
Temperature of the peak maximum [°C]	81.75	239.81
Temperature of the peak onset [°C]	79.74	188.50
Heat of transition [J·g^{-1}]	133.4	419.6

The detonation velocity was also measured. TNT loads at bulk density were placed in a PVC sheath with an internal diameter of 30 mm and an external diameter of 45 mm. The sensors were located at a distance of 30 mm. A hexogen igniter with an ERG fuse was used to initiate the charges. Two variants of measurements were made; with bulk density TNT (Table 3) and in a system in which the TNT was submerged in water (Table 4).

Table 3. Detonation velocity for dry TNT

Sample No.	Density [g·cm^{-3}]	Load diameter [mm]	Detonation velocity [m·s^{-1}]
1	0.83	30	3190
2	0.87	45	3700
3	0.78	30	2940
4	0.75	45	2900
5	0.59	30	3270

Table 4. Detonation velocity for TNT submerged in water (approx. 30% water) for a 45 mm diameter load

Sample No.	Density [g·cm^{-3}]	Detonation velocity [m·s^{-1}]
1	1.05	4030
2	1.10	4890
3	1.00	4010
4	0.91	3130

The results of detonation measurements correspond to those obtained by other authors. They indicate, *inter alia*, the detonation ability of washed out TNT in the case of submerging it in water.

7. Possible reuses of washed out TNT

An important issue related to washing out TNT is developing a method for its use or disposal without causing environmental pollution. One of the “clean” uses of such TNT is to utilise it as a component of mining explosives or as an independent blasting agent. TNT is added to loose mining explosives in a comminuted form. Therefore, a small fraction of washed out TNT with a fineness of about 0.3 mm, could be used in such materials. The high-energy supplement should undoubtedly be dried beforehand. On the other hand, in the case of suspension explosives, larger fractions of TNT may be used. TNT does not need to be dried; however, the water content, which should be included in the potential composition of the suspension explosive, must be determined.

One possible use of TNT is in its addition to emulsion explosives. In some solutions it is used as a component of the organic continuous phase. It can also potentially be added as a high energy combustible component. However, this solution is very rarely used due to the TNT oxygen imbalance. Emulsion explosives, which contain large amounts of TNT can be used in surface mining, where the oxygen balance of the blasting agent affecting the content of toxic compounds in the reaction products is not taken into account.

In addition to the use of TNT in explosive mining mixtures, it can be utilised as an independent blasting agent. In this case, it is loaded into the lower, most frequently water-containing section of the blast hole. The upper part of the blast hole, above the water level, can be charged with a non-waterproof mixture of TNT and ammonium nitrate(V) (NH_4NO_3). By changing the consistency of the components in the nitrate, it is possible to regulate the detonation parameters of the explosive mixture to a larger extent.

One of the possibilities of using TNT as a mining blasting agent is the production of boosters. The boosters are employed as indirect charges to initiate mining explosives that are not capable of detonating from using various types of detonators or the detonating cord. For some time, it has been accepted in blasting works that the booster, in addition to being made of HE, should have a large mass. Therefore, boosters produced from TNT have become popular, because the cost of the utilised explosive material is very important.

8. Summary

Based on the analysis of the results of the tests carried out in the field and under laboratory conditions, the following conclusions can be drawn regarding the use of high-pressure water jets for detaching and washing out of TNT from artillery shells:

8.1. The use of a water jet parallel to the axis of symmetry of the projectile shell, without causing a change in its spray angle, provides satisfactory results only when removing TNT from smaller caliber artillery shells (*e.g.* 85 mm).

8.2. In order to increase the effectiveness of washing out TNT from larger caliber projectiles, variable spray angles, as well as a working head with two nozzles positioned relative to each other, should be used.

8.3. Increasing the pressure of the water jet is the most effective way to increase the efficiency of the process of washing out TNT. Furthermore, it provides better quality of eroded surfaces and effectiveness of cleaning of the inside of the shells.

8.4. The process of washing out TNT should be carried out in a way which does not result in the loss of kinetic energy of the stream to unnecessary heating of the shell, which causes undesirable melting of the TNT layers adjacent to it.

8.5. The comparison of the efficiency of hydrofluid removal of substitute explosive material from the shells to the effectiveness of washing out of real TNT, indicates that there is a need for the multi-criteria optimisation of this approach for cleaning artillery shells.

8.6. Depending on the conditions of washing TNT from artillery shells, there are three different forms of particles: a porous "foam" formed from the finest agglomerated particles, "grits", which is the largest group of TNT particles with a size of #5-15 mm and large-size TNT labels melted by a hot shell.

8.7. The conditions for effective washing out of TNT from typical artillery shells were analysed and an outline of the mechanism determining the effectiveness of this process was developed.

8.8. The use of a multi-socket technological device for hydrofluidic washing out of explosive materials will allow for multiplication of the process efficiency in proportion to the number of simultaneously utilised working sockets.

8.9. TNT grains washed out by this hydro-jet method are useful in several ways, mainly in the mining industry.

8.10. On the basis of a comparative analysis of various methods used to remove explosive materials from shells, it was found that the developed hydrofluidic method is faster, more efficient and much more economical than the other available approaches.

Summarising the achievements in this area, it can be concluded that the results of previous research on washing out TNT from shells, which was carried out using high-pressure water jets, whose selection was based on the technology developed at the Institute of Unconventional Hydrostatic Technologies of the Koszalin University of Technology, are very promising.

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