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Technological Problems Encountered During the Elaboration of a Warhead Component with a Diaphragm

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Abstract: This paper presents a method for pressing a small shaped piece with a diaphragm made from light inertial material, intended for use as a tandem shaped charge principal warhead. The general requirements for the pressing moulds are shown. The pressing method for the small shaped piece is described with the use of the high explosive OKFOL. It concerns the pressed explosive mass, the method of mould lubrication, pressing pressure, the number of pressing steps, the method of removal of the pressed small shaped piece from the mould, and the proportions of the granulated to crushed OKFOL and its density after pressing. Very high, measured densities of the pressed OKFOL in the small shaped piece at different cross-sections (bottom − top of the shaped piece) 1.761-1.813 g/cm^3, *i.e.* (95.5-98.3)% of the calculated theoretical density of 1.84 g/cm^3 were obtained for the explosive with a phlegmatizer content of 3.6%. During the trials the following damage can occur: cracking along the side of the cone, breaking off of some of the cylinder surface, breaking away of the shaped piece bottom during extraction. The accuracy of the shaped pieces produced, particularly their coaxiality, ensured the proper function of the tandem shaped charge warhead.

Keywords: shaped charge, elaboration of the charge with explosive, pressing of explosive

Introduction

The presently used Light Fighting Vehicles type BWP-1 and heavy armoured type tank are equipped with add-on explosive reactive armour (ERA) made of reactive cassettes [1-3]. However, this does not protect them from destruction by the tandem shaped charge warheads of high penetration capability *DP* (depth of penetration) [4-7].

Warhead 1 (precursor) in a tandem shaped charge warhead is usually a small shaped charge or an explosively formed projectile (EFP) charge, whose task is to destroy the ERA armour [8]. It functions by:

1. initiating detonation of the explosive (EX) contained in the reactive cassette, protecting the basic Rolled Homogeneous Armour (RHA) of the fighting vehicle, or
2. boring a hole in the reactive cassette, of possibly large diameter, without initiating the explosive.

The jet of warhead 2 (principal), containing a large shaped charge, initiated with proper delay after the initiation of the precursor, penetrates the basic armour of the fighting vehicle at a point in the detonated cassette or through the hole bored in it (Figure 1) [7].

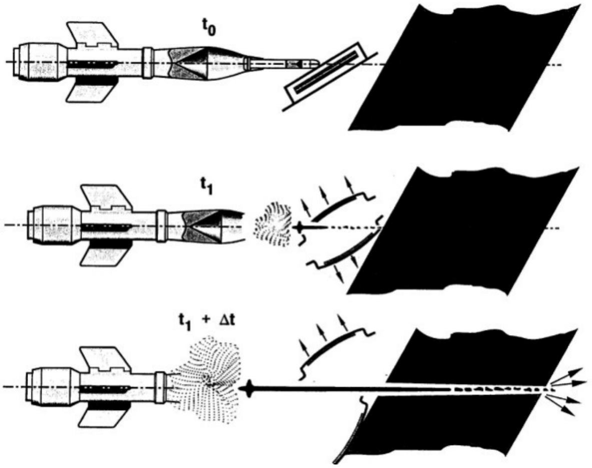

Figure 1. Mechanism of action of the tandem shaped charge warhead: 1 − warhead 1 (precursor), 2 − warhead 2 (principal), 3 − reactive cassette ERA, 4 − basic armour RHA.

The shaped charge of warhead 2 (principal) consists of a small shaped piece made of pressed explosive with an inertial element (a diaphragm made from light inertial material) and a large shaped piece with a liner (Figure 2) [9, 10]. The detonation wave occuring after initiation of the small shaped piece is directed at the large shaped piece for the purpose of its initiation. The shaped charge jet generated by detonation of the principal warhead is able to penetrate the basic armour.

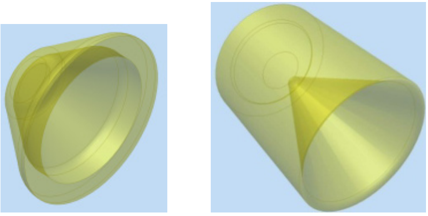
a b

Figure 2. Appearance of the shaped pieces: small (a) and large (b) of warhead 2 of the tandem shaped charge warhead.

The precise performance of the small and the large shaped pieces and their assembly in warhead 2 (Figure 3) with control of their coaxiality, enables proper penetration of the shaped charge jet through the RHA.

Various methods of explosive pressing, used for shaped charges, are described in references [11-16]. The present paper focuses on the problems which arise while developing the technology for the elaboration of the small shaped piece of warhead 2 (principal) with an inertial element, using a method of explosive pressing in a mould.

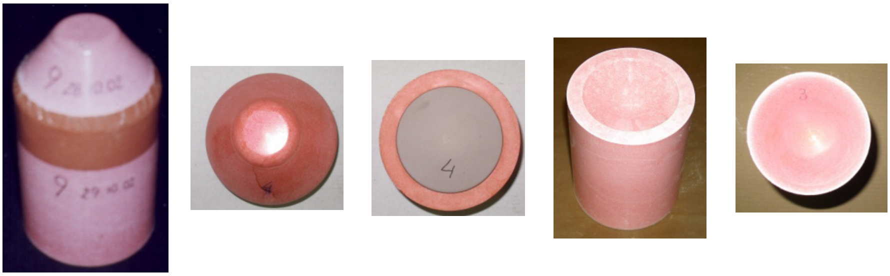
a b c d e

Figure 3. Warhead 2 (principal) of the tandem shaped charge warhead: (a) small and large shaped pieces, (b) small shaped piece – top view, (c) small shaped piece with diaphragm – bottom view, (d) large shaped piece – top view from the small shaped piece side, (e) large shaped piece (without a liner) – bottom view.

Experimental

Mould parameters for pressing the explosive shaped pieces

The moulds for pressing have to fulfil high requirements of coaxiality of the liner cone with the surface of the principal charge, of both the small and the large shaped pieces, as well as coaxiality of the diaphragm with both of the shaped pieces of the charge. Mould 1 for pressing the small shaped piece (Figure 4) consists of the following parts:

a. a female mould for the shaped piece take up,
b. a base, bush and stamp, forming all surfaces of the shaped piece,
c. a limiter, ensuring equal height of the shaped piece,
d. so called forks, enabling pressing from both directions,
e. handles for manipulation of the mould.

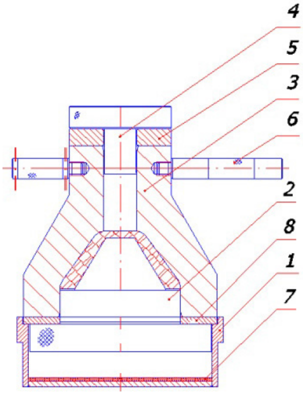

Figure 4. Mould 1 for pressing of the small shaped piece of warhead 2 of the tandem shaped charge warhead with the female mould (receiver): 1 − female mould (receiver), 2 − base of the mould, 3 − bush, 4 − stamp, 5 − limiter, 6 − handle, 7 − amortizing insert, 8 − fork.

The components of mould 1 were made with high linear (± 0.01 mm) and angle (single minutes) accuracy, from high quality steel of > 45 HRC hardness, which was thermally improved, hardened and polished to achieve a high degree of smoothness.

Preparation of the explosive for pressing of the small shaped charge of warhead 2

The functioning of the explosive charges is highly dependent on the method of preparing their composition, *i.e.* testing of components, their mixing, crushing, granulating and drying. For all components the following parameters are determined: chemical purity, moisture content, presence of undesirable impurities, temperature of melting, thermal stability (75 °C within 48 h), design conformity of the components (reactivity) within the range of temperatures used, lack of reactivity of the components of the mixture with the material of the warhead housing.

Crushing reduces the grain size of the material, develops the active surface of the particles and is the first step in the preparative process for the components of the explosive mixtures. For this purpose roller frames, ball mills, percussive crushers, press rollers, disintegrators, *etc*. may be applied, depending on the type of explosive mixture. Inorganic oxidants are dried at 70-80 °C, ground and dried again. Then the material is sieved to a uniform fraction and separated from adventitious contamination. It is essential to mix the dry components to obtain a homogeneous mixture and to develop a specific surface area, ensuring proper chemical reaction of the explosive charge. Organic additives in solution are often used for the preparation of explosive mixtures; they facilitate the achievement of homogeneity after evaporation of the solvents and, as a result of the agglomeration of particles, increase their adhesion.

The method of manual mixing by means of different sieves is still used, where the preliminarily prepared mixture is rubbed through them. The function of the first sieve, a coarse one of mesh slightly greater than the grain size of the coarsest component of the mixture, is to break up lumps and ensure proper mixing. Then the mixture is rubbed 2-5 times through the finer sieves. The uniformity of the composition obtained may be checked by gentle and careful smearing of a sample, put onto a soft rubber pad using a wooden or plastic spatula. The surface of the thin layer must be smooth without visible oversized grains.

For the preparation of explosive mixtures on a larger scale various mixers (drums, drums with balls, cochlears, planetary), Werner & Pfleiderer kneaders, press rollers, *etc*. can be used.

The next step of the process is granulation of the mixture, by mixing the wet or moistened mixture, rubbing it through a sieve, partly drying and rubbing away. As a result of granulation the mixture becomes uniformly granular and free flowing, enabling volumetric dosage into the mould.

Drying off of the solvent introduced during the mixing with the dissolved organic additive is the final stage of the process. Usually it requires several hours at 35-40 °C, and the residual solvent and moisture in the mixture should not exceed 0.65%.

Pressing of the small shaped piece of warhead 2

The high penetration capability *DP* of the RHA by the shaped charge warhead, is provided by the use of a high explosive, *e.g*. octogen phlegmatized (with wax, Teflon, *etc*.), for the pressed shaped pieces of the warhead. The phlegmatizer content of density ρ_{phl} in the mixture may amount to a = (3-6)%. The explosive density ρ_{EX} in the pressed shaped piece should be as large as possible, however in practice it is smaller than the maximum theoretical density ρ_{EXmax}, which is determined from the equation:

$$1/\rho_{EXmax} = (1 - a) / \rho_{EX} + a / \rho phl \tag{1}$$

For example, on the assumption that the density of octogen $\rho_{EX} = 1.91$ g/cm^3 and with 3.6% phlegmatizer content in the mixture (a wax of $\rho = 0.9$ g/cm^3), the calculated theoretical maximum density of the phlegmatized octogen amounts to $\rho_{EXmax} = 1.84$ g/cm^3 [8, 9].

The technology of the shaped piece for warhead 2 elaboration was developed in the industrial plant. This included preparation of the explosive, construction of the mould, determination of the pressing parameters and the inspection method for the shaped pieces obtained. The shaped pieces of warhead 2 (Figure 2a) were made using an hydraulic press at >160 T pressure.

Various proportions of granulated and crushed explosive and different pressing parameters were applied, aiming to approach the theoretical density for the shaped pieces, *e.g.* made from OKFOL [17] (Figure 5).


a b

Figure 5. The explosive (OKFOL) for pressing: (a) granulated, (b) crushed.

Different lubricants (liquid, powder) were applied depending on the kind of explosive and the surface of the mould used. Figure 6 shows parts of mould 1, prepared for filling.

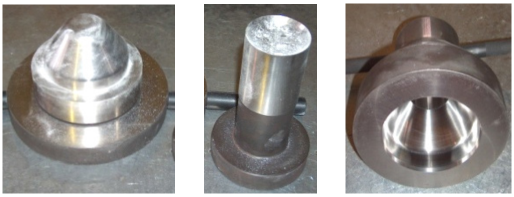
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Figure 6. Parts of mould 1 of warhead 2: (a) base of the mould, (b) stamp, (c) bush.

The lubricated mould parts were assembled on the so-called 'cart' of the press. Three forks, two of which so-called 'distance forks' and a so-called 'technological fork', were put on the base of mould 1, (Figure 7), and the bush was placed on them. The assembled mould was filled with the explosive (Figure 8).

Figure 7. Base of mould 1 with the 'distance forks' on the press cart.

Figure 8. Mould 1 prepared for filling with the explosive.

Next, the stamp and the limiter, ensuring constant height of the shaped pieces, were inserted into the mould (Figure 9a), the two 'distance forks' were taken out, giving technological space (Figure 9b), eventually the 'cart' with the mould was put under the press.

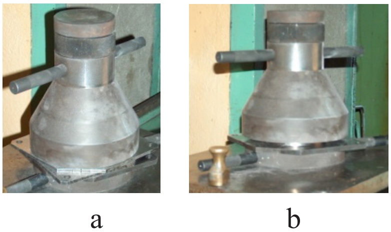

Figure 9. Mould 1 before pressing: (a) inserted stamp and limiter, (b) the two 'distance forks' removed.

Degassing of the small shaped piece was achieved by application of a number of pressing steps and pressure values. After many trials, carried out using different parts of the final mould, arrangements for triple pressing were obtained (Tables 1 and 2).

After pressing, the 'cart' with mould 1 including the pressed shaped piece was taken out from under the press (Figure 10), the limiter and the 'technological fork' were removed, and finally mould 1 was inserted into the female mould (receiver) for shaped piece ejecting (Figure 11).

Approximately constant density distribution in the whole volume of the pressed shaped piece is only possible with isostatic pressing. However, here only pieces of uncomplicated shape are involved. The most uniform distribution of density can be obtained when pressing *e.g.* cylinder, in which the diameter is similar to the height. The pressing is then comparable to isostatic pressing, and sieved material can fill up the female mould quite uniformly. Figure12 shows the pressed shaped piece in the female mould.

Figure 10. Mould 1 after pressing of the shaped piece.

Figure 11. Mould 1 prepared for ejecting of the shaped piece.

Figure 12. Pressed shaped piece in the female mould 'take up'.

The properties of the explosive powder, *e.g.* moisture content and uniform powder distribution and the manner of filling the mould, are significant parameters for the technology of pressing. This is particularly important while pressing pieces with changing shape and cross-sectional area with the height, when a local increase in density, *e.g.* in the conical parts, may occur. This may cause galling of the mould, difficulty or even preclusion of its opening without violent action, in the worst cases causing damage to the polished parts. Generally, pressing operations need to be done with caution, and particularly whilst attempting to open the galled mould when the risk of initiation of the enclosed explosive is very high. Therefore, selection of the mould material, the kind of thermal processing, tolerances and distances between the parts fitting together, and the roughness of their surface, *etc*. are essential aspects.

The optimized process for the pressing of a complicated form of shaped piece decreases to a minimum the potential problems described above, and the density obtained in the shaped piece changes minimally along the axis and perpendicularly to it, or changes according to the assumption. For pressing of high density shaped pieces of complicated form and large size from high explosives, it is essential to determine the number and thickness of the forks, their location in the bottom and upper parts of the mould, and the order of their removal.

During pressing all elements of the process should be controlled: a completeness of the mould closing, the wear on individual parts, the conditions which can cause galling of the mould, not exceeding the permissible deformation of the pressed material, *etc*.

The principal objective, which enables the high energy of the shaped charge jet to be achieved, and the same high perforation capability of the RHA, is to obtain the highest density of the pressed shaped piece and the required distribution of this density. This is possible on the assumption that both the construction of the pressed shaped pieces (the liner, the diaphragm, the method of initiation), and the entire tandem shaped charge warhead (length of the ballistic cap, type of housing, *etc*.) is optimal. By contrast, an increase in the density of the pressed shaped piece and the use of a liner which is *e.g*. too thin, would cause a decrease in the RHA perforation capability of the jet of such a warhead.

In Table 1 the parameters for pressing the small shaped piece of warhead 2, using sulphur instead of explosive material, are presented. The aim of using this inert material is to establish the preliminary parameters of the process and other aspects leading to the safe elaboration of explosive material in a further step; sulphur is commonly used for this purpose.

The material for pressing was prepared from sulphur in granulated form and sulphur obtained by crumbling of previously pressed shaped pieces, and both single and double pressing was applied. The shaped piece obtained corresponded exactly to the internal shape of the mould, was of suitable height and had no cracking on its surface.

Table 1. Pressing parameters for shaped pieces using sulphur

<table>
<tr><th>No.</th><th>Mass of material, m_{EX}, [g]</th><th colspan="2">Pressure/Time of pressing, p/t, [MPa/s]</th><th>Density of the shaped piece ρ, [g/cm^3]</th><th>Height of the shaped piece, h, [mm]</th></tr>
<tr><td rowspan="2">1</td><td>>160</td><td colspan="2">20/10</td><td>1.670</td><td>>54.00</td></tr>
<tr><td colspan="5">Mould was not closed completely, clearance of ≠2 mm. Cracked shaped piece.</td></tr>
<tr><td rowspan="2">2</td><td>>160</td><td>10/10</td><td>20/10</td><td>1.675</td><td>>54.00</td></tr>
<tr><td colspan="5">50% of granulated sulphur. The shaped piece was without defects.</td></tr>
<tr><td rowspan="2">3</td><td>>160</td><td colspan="2">30/10</td><td>1.682</td><td>>54.00</td></tr>
<tr><td colspan="5">50% of granulated sulphur. Mould was not closed completely, clearance of ≠ 1.5 mm.</td></tr>
<tr><td rowspan="2">4</td><td>>160</td><td colspan="2">30/10</td><td>1.683</td><td>>54.00</td></tr>
<tr><td colspan="5">100% of crumbled sulphur. Mould was not closed completely, clearance of ≠ 1.5 mm.</td></tr>
</table>

In Table 2 the results of pressing a small shaped piece using OKFOL are presented. Contrary to published work [11-16] multiple pressing was applied, with increased pressure on the stamp and maintaining the material under pressure for 10-20 s. In the first trials the mass of the explosive was varied, the density of the entire shaped piece, and of its individual components, and also the closing of the mould, were controlled. Particular attention was paid to maintaining the density of the explosive below the critical level, which for OKFOL amounts to *ca*. 99% of the theoretical density, and to obtaining, if possibly, uniform distribution of density in the individual components of the shaped piece.

This can be achieved by applying suitable forks while filling the female mould and pressing. A difficult problem was encountered during disassembly of the parts of mould 1, when often cracking of the pressed shaped piece occurred. To prevent crumbling of the internal bottom edge of the shaped piece, lubrication of the mould was changed, *e.g*. by application of powder and liquid on its various surfaces. After many attempts the explosive mass was determined as <180 g, achieved by changing only the manner of lubricating the surfaces of mould 1, the number of pressings and the pressing pressure. As a result, the parameters were optimized and shaped pieces without defects were obtained, together with a suitable distribution of explosive density and of assumed repeatable height.

Table 2. Pressing parameters for shaped pieces using OKFOL

<table>
<tr><th>No.</th><th>Mass of material, m_{EX}, [g]</th><th colspan="2">Pressure/Time of pressing, p/t, [MPa/s]</th><th colspan="2">Density of the shaped piece ρ, [g/cm^3]</th><th>Height of the shaped piece, h, [mm]</th></tr>
<tr><td rowspan="2">1</td><td>>160</td><td>7/10</td><td>20/10</td><td>1.801</td><td>1.710</td><td>>54.00</td></tr>
<tr><td colspan="6">Granulated explosive. Number of forks: during filling three forks (7.8 mm, 5.6 mm, 4.8 mm), pressing with a fork of 7.8 mm thickness at the bottom of the mould. The shaped piece was without defects, the height was too large.</td></tr>
<tr><td rowspan="2">2</td><td>>170</td><td colspan="2">25/10</td><td colspan="2">1.747</td><td><52.00</td></tr>
<tr><td colspan="6">Granulated explosive. Number of forks as in item 1. Crumbled cylindrical surface, bottom torn off while ejecting.</td></tr>
<tr><td rowspan="2">3</td><td>>170</td><td colspan="2">25/10</td><td colspan="2">1.749</td><td><52.00</td></tr>
<tr><td colspan="6">Granulated explosive. Number of forks as in item 1. Cracking along the side element of the cone, crumbled cylindrical surface.</td></tr>
<tr><td rowspan="2">4</td><td>>170</td><td colspan="2">25/10</td><td colspan="2">1.751</td><td><52.00</td></tr>
<tr><td colspan="6">50% of granulated explosive. Number of forks as in item 1. The shaped piece was too crisp and broken.</td></tr>
<tr><td rowspan="2">5</td><td>>170</td><td colspan="2">25/10</td><td colspan="2">1.744</td><td><52.00</td></tr>
<tr><td colspan="6">50% of granulated explosive. Number of forks as in item 1. The shaped piece crumbled while ejecting.</td></tr>
</table>

<table>
<tr><th>No.</th><th>Mass of material, m_{EX}, [g]</th><th colspan="3">Pressure/Time of pressing, p/t, [MPa/s]</th><th colspan="4">Density of the shaped piece ρ, [g/cm^3]</th><th>Height of the shaped piece, h, [mm]</th></tr>
<tr><td rowspan="2">6</td><td>>170</td><td colspan="3">25/10</td><td colspan="4">1.748</td><td><52.00</td></tr>
<tr><td colspan="9">Granulated explosive. Number of forks as in item 1. The shaped piece was without defects.</td></tr>
<tr><td rowspan="2">7</td><td>>170</td><td colspan="3">25/10</td><td colspan="4">1.746</td><td><52.00</td></tr>
<tr><td colspan="9">Granulated explosive. Number of forks as in item 1. Crumbled cylindrical surface.</td></tr>
<tr><td rowspan="2">8</td><td>>170</td><td colspan="3">30/10</td><td colspan="4">1.748</td><td><52.00</td></tr>
<tr><td colspan="9">50% of granulated explosive. Number of forks as in item 1. Bottom of the shape piece was torn off while ejecting.</td></tr>
<tr><td rowspan="2">9</td><td>>170</td><td>10/10</td><td colspan="2">25/10</td><td colspan="4">1.747</td><td><52.00</td></tr>
<tr><td colspan="9">50% of granulated explosive. Number of forks as in item 1. During filling two forks at the bottom of the mould, during pressing 1 – with both forks, during pressing 2 – with one fork. Crumbled shaped piece while ejecting.</td></tr>
<tr><td rowspan="2">10</td><td>>170</td><td>30/10</td><td colspan="2">32/10</td><td colspan="4">1.749</td><td><52.00</td></tr>
<tr><td colspan="9">50% of granulated explosive. Number of forks as in item 1. The shaped piece cracked along the side element of the cone.</td></tr>
<tr><td rowspan="2">11</td><td>>170</td><td>25/10</td><td colspan="2">32/10</td><td>1.797</td><td>1.778</td><td>1.735</td><td>1.763</td><td><52.00</td></tr>
<tr><td colspan="9">50% of granulated explosive. Number of forks as in item 1. The shaped piece was without defects.</td></tr>
<tr><td rowspan="2">12</td><td>>170</td><td>25/10</td><td>28/10</td><td>30/10</td><td colspan="4">1.775</td><td><52.00</td></tr>
<tr><td colspan="9">50% of granulated explosive. Number of forks as in item 1. Cracking along the side element of the cone, a little crumbling on the cylindrical surface (or torn off the bottom while ejecting – in other shaped pieces).</td></tr>
<tr><td rowspan="2">13</td><td>>170</td><td>25/10</td><td>28/10</td><td>30/10</td><td>1.803</td><td>1.787</td><td>1.746</td><td>1.77</td><td><52.00</td></tr>
<tr><td colspan="9">Granulated explosive. Number of forks as in item 1. The shaped piece was without defects.</td></tr>
<tr><td rowspan="2">14</td><td>>170</td><td>25/10</td><td>28/10</td><td>30/10</td><td colspan="4">1.780</td><td><52.00</td></tr>
<tr><td colspan="9">Granulated explosive. Number of forks as in item 1. The shaped piece crumbled slightly while ejecting.</td></tr>
<tr><td rowspan="2">15</td><td>>170</td><td>25/10</td><td>28/10</td><td>30/10</td><td colspan="4">1.775</td><td><52.00</td></tr>
<tr><td colspan="9">Granulated explosive. During filling – three forks (7.8 mm, 5.6 mm i 4.8 mm), during pressing – fork of 7.8 mm thickness. The shaped piece crumbled while opening the mould.</td></tr>
<tr><td rowspan="2">16</td><td>>170</td><td>25/10</td><td>28/10</td><td>30/10</td><td>1.761</td><td>1.786</td><td>1.813</td><td>1.781</td><td><52.00</td></tr>
<tr><td colspan="9">Granulated explosive. Number of forks as in item 1. The shaped piece was without defects.</td></tr>
<tr><td rowspan="2">17</td><td>>170</td><td>25/10</td><td>28/10</td><td>30/10</td><td colspan="4">1.777</td><td><52.00</td></tr>
<tr><td colspan="9">50% of granulated explosive. Number of forks as in item 1. The shaped piece was without defects.</td></tr>
</table>

No.	Mass of material, m_{EX}, [g]	Pressure/Time of pressing, p/t, [MPa/s]			Density of the shaped piece ρ, [g/cm^3]		Height of the shaped piece, h, [mm]
18	>170	25/10	28/10	30/10	1.779		<52.00
	Granulated explosive. During filling - three forks, during all three pressings only the fork of 7.8 mm thickness. **The shaped piece was without defects.**						
19	>170	25/10	28/10	30/10	1.780		<52.00
	From 30% to 50% of granulated explosive. During filling and pressing 1 − three forks, during pressings 2 and 3 − with fork of 7.8 mm thickness. **The shaped piece was without defects.**						
20	>170	25/10	28/10	30/15	1.774	1.788	<51.60
	50% of granulated explosive. Number of forks as in item 1. The bottom was torn off while ejecting by the press.						
21	>170	25/10	28/10	30/15	1.763		<52.00
	50% of granulated explosive. Number of forks as in item 1. **The shaped piece was without defects.**						
22	>170	25/10	28/10	30/20	1.771		<51.50
	Crushed explosive. Number of forks as in item 1. The conical outer surface of the shaped piece was of high roughness, the bottom inner edge of the cylinder was too soft.						
23	>170	25/10	28/10	30/20	1.774		<51.50
	50% of granulated explosive. Number of forks as in item 1. **The shaped piece was without defects.**						
24	>170	28/10	30/10	32/10	1.780		<51.50
	50% of granulated explosive. Number of forks as in item 1. Crushed cylindrical surface.						

In order to achieve maximum density of the OKFOL, apart from increasing the pressure, the pressing time was extended, whilst checking if the large shaped charge obtained was complete.

In order to check the correctness of the construction and the developed technology of elaboration, the shapes pressed in the method described above, were assembled in tandem shaped warheads. For testing on the firing range, each tandem shaped warhead was placed at optimal distance from the RHA (Rolled Homogeneous Armour) and perpendicularly to it, and was fired using an electric detonator. After every test the depth of the RHA penetration (*DP*) was measured [8, 9].

Conclusions

On the basis of the pressing trials carried out it can be stated that:

1. The use of sulphur as an inert material in the first part of the trials enabled the preliminary pressing parameters to be determined, using crushed material obtained from earlier pressed shaped pieces, and the use of multiple pressing.
2. Good distribution of density in the pressed explosive was achieved, even while pressing such a complicated element as the small shaped piece of warhead 2 of the tandem shaped charge.
3. Very high measured densities of pressed OKFOL in the small shaped piece at different cross-sections (bottom − top of the shaped piece) 1.761-1.813 g/cm^3, *i.e.* (95.5-98.3)% of the calculated theoretical density of 1.84 g/cm^3 were obtained for the explosive with a phlegmatizer content of 3.6%.

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