Influence of components on the fabrication and ballistic characteristics of MC explosives

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ABSTRACT

This paper presents research outcomes regarding the influence of formulation components on the fabrication process and detonation characteristics of MC explosives. Experimental findings indicate that Serezin M75 is an optimal phlegmatizer for the production of MC explosives. The primary components—TNT, RDX, and aluminum (Al) powder—directly dictate the ballistic properties of the composite explosive. A formulation comprising (19 ± 2)% TNT, (57 ± 3)% RDX, and (17 ± 2)% Al yields detonation parameters equivalent to those of foreign reference samples. Specifically, the formulation with a mass ratio of TNT : RDX : Al : Phlegmatizer at 19 : 57 : 17 : 7 exhibits superior technological rheology, consistently achieving a casting density exceeding 1.7 g/cm³.

Keywords: MC explosive; TNT; RDX; Aluminum powder; Detonation velocity; Explosive work.

1. INTRODUCTION

MC explosive, a powerful composite explosive utilized in the Russian Navy (abbreviated from the Russian term морская смесь - marine mixture), was originally manufactured in the Soviet Union as a main charge for torpedoes, naval mines, and naval missile warheads [1]. According to published literature, the nominal composition of MC explosive comprises 57% RDX, 19% TNT, 17% aluminum powder, and 7% phlegmatizers and processing additives [2]. Within this matrix, TNT serves as the energetic binder, providing the necessary thermal energy and fluid medium to disperse solid components (RDX and Al powder), thereby facilitating the melt-casting process into munitions. RDX functions as the primary high-energy constituent, governing the overall brisance of the MC explosive. Aluminum powder participates in secondary post-detonation reactions, particularly in underwater environments, which significantly enhances the total heat of explosion.

Phlegmatizers are incorporated to desensitize the explosive mixture and improve the rheological properties during melt-casting [3]. Additionally, minor quantities of additives are required to prevent phase separation among TNT, RDX, and the phlegmatizer. Research indicates that the detonation process of TNT-Al explosives occurs in two distinct stages. The first stage involves the primary detonation of RDX. The second stage is characterized by the secondary combustion of Al particles with the gaseous detonation products. During the first stage, increasing the Al mass fraction inadvertently decreases the detonation velocity of the TNT matrix due to a reduction in detonation pressure and a lower reaction rate within the Chapman-Jouguet (C-J) zone. In the second stage, the ignition delay of Al is approximately 0,91 μs post-detonation. Furthermore, a substantial mass of Al reacts with the expansion products after 1,33 μs. This implies that the combustion of Al powder predominantly occurs behind the C-J plane during the expansion phase of the gaseous products; consequently, higher Al concentrations prolong the ignition activation time [3].

Literature values establish that the detonation velocity of MC explosive reaches 7600 m/s at a density of 1,70 g/cm³, with a heat of explosion of 1409 kcal/kg [2]. The baseline technical specifications of foreign MC explosive samples are presented in Table 1.

Table 1. Technical specifications of a foreign MC explosive sample.

No.	Parameter	Unit	Result
1	Ballistic mortar work capacity	% TNT	136,8
2	Detonation velocity	m/s	7.554
3	Lead cylinder compression (50g mass, 1.1 g/cm³ density)	mm	19,5
4	Impact sensitivity (CAST method)	%	20

Although the nominal single-component formulation of MC explosive has been published, variances in the quality of domestic raw materials compared to original foreign counterparts necessitate a standardized empirical evaluation. Specifically, the influence of phlegmatizers and aluminum powder on the detonation characteristics must be systematically assessed to enable the domestic fabrication of MC explosives that meet or exceed international quality specifications [4-11].

2. MATERIALS AND METHODS

2.1. Research subjects

The study focuses on evaluating the detonation characteristics-specifically detonation velocity, heat of explosion, work capacity (via ballistic pendulum), lead cylinder compression, and impact sensitivity-of both reference foreign MC explosive samples and domestically fabricated samples with varying formulations and component ratios.

2.2. Materials, chemicals, and equipment

**Materials and chemicals*

Military-grade TNT; military-grade RDX; aluminum powder with varied average particle size distributions (≤ 5 µm, 10-25 µm, and 40-80 µm, USA); Serezin M-75 (dropping point 75–80 °C, Russian Federation); Ozone Wax (Thailand); Palmowax SF (melting point 141-145 °C, Malaysia); Wax E (melting point 80–85 °C, USA); Wax O (Oleamide) (melting point 68–72 °C, USA); Cetyltrimethylammonium Bromide (CTAB) (Netherlands).

**Equipment and apparatus*

- Fabrication and casting equipment: Double-jacketed stainless steel reactor, IKA overhead stirrer; thermostatic heating circulator; cylindrical mold assembly (double-jacketed) with hermetic seals; GT08 pneumatic vibrator; vacuum pump; analytical balance.

- Measurement and testing instruments: Kast drop-weight impact sensitivity apparatus; ballistic pendulum for measuring explosive work capacity; lead cylinder compression test setup; Kontinitro SA EXPLOMET 2 chronometer for detonation velocity; OZM DCA-5 explosion calorimeter system (Czech Republic); Dahometer DH-2000 densitometer.

2.3. Research methodology

- Fabrication of composite explosive: MC explosive was formulated under laboratory conditions utilizing a thermostatic circulator pumping a heat transfer fluid into the jacket of the stainless steel reactor. The entire predetermined mass of phlegmatizer and additives was charged into the reactor, and the temperature was ramped to 95 °C. Upon complete fusion of the phlegmatizer, the designated mass of TNT was introduced. The overhead stirrer was activated to homogenize the mixture. Once the TNT-phlegmatizer matrix became completely molten, RDX was incrementally fed into the mixing vessel. After visual confirmation that no agglomerates remained, the aluminum powder was gradually added. Continuous mechanical stirring was maintained to yield a highly homogeneous MC explosive dispersion.

- Determination of detonation characteristics: Parameters including casting density, detonation velocity, ballistic pendulum work capacity, and lead cylinder compression were quantified at the Explosives Measurement Center (Institute of Propellants and Explosives). Specifically:

+ Charge density was measured using a Dahometer DH-2000 densitometer (measuring capacity up to 2000 g, resolution 0.001 g/cm³).

+ Work capacity (ballistic pendulum) was determined in accordance with the TCVN 6424:1998 standard.

+ Lead cylinder compression was tested following the TCVN 6421:1998 standard.

+ Impact sensitivity was evaluated using the Kast drop-weight apparatus per the TCVN/QS 1837:2017 military standard.

+ Detonation velocity was determined using a high-speed chronometer measuring the transit time of the detonation wave across a defined length of the explosive column.

- Heat of explosion samples were submitted for calorimetric analysis at the Weapons Technical Center, Military Technical Academy.

3. RESULTS AND DISCUSSION

3.1. Selection of phlegmatizers

Literature indicates that Serezin is the conventional phlegmatizer employed in MC explosives. Chemically, Serezin is a mixture of long-chain aliphatic hydrocarbons with an average molecular formula of C_nH_{2n+2}, where the coefficient n typically ranges from 30 to 50. Consequently, its thermo-physical properties vary significantly depending on the carbon chain length. The melting point directly governs its thermal fusion capability, which subsequently dictates the technological rheology during the melt-cast compounding process. Furthermore, the molecular composition influences the overall thermodynamic energy output of the explosive. Therefore, empirical testing is required to identify a Serezin grade that offers optimal processability. To ensure high technological viability, the phlegmatizer must demonstrate excellent miscibility and compatibility with the other constituents. The fluid continuous phase of the MC explosive consists exclusively of the molten phlegmatizer and TNT.

The research group investigated five distinct phlegmatizers: Serezin M75, Ozone Wax, Wax O, Palmowax SF, and Wax E. Based on the nominal MC composition (57% RDX, 19% TNT, 17% Al, and 7% phlegmatizer), RealWin thermodynamic simulation software was utilized to theoretically predict the detonation products for each variant. The results are summarized in Table 2.

To compute the theoretical heat of explosion for the composite mixtures, the following thermodynamic relation was employed:

$$Q_n = Q_{spn} - Q_{tn}$$

Where:

$$Q_{spn} = \sum X_m(\Delta H_f^{298})_m$$

$$Q_{tn} = \sum C_n(\Delta H_f^{298})_n$$

- X_m: Mass fraction of component m in the detonation products;
- C_n: Mass fraction of component n in the composite explosive;
- $(\Delta H_f^{298})_m$: Enthalpy of formation of component n in the detonation products;
- $(\Delta H_f^{298})_n$: Enthalpy of formation of component n in the explosive composition.

Based on these thermochemical calculations, the theoretical heat of explosion for the formulations containing different phlegmatizers is presented in Table 3.

Thermodynamic analysis demonstrates that Serezin M75, representing an alkane mixture with longer carbon chains, inherently yields a higher heat of explosion compared to the shorter-chain Ozone Wax. Phlegmatizer groups containing NO functional groups within their molecular structure universally tend to depress the total heat of explosion.

Table 2. *Predicted detonation products of the composite explosive using various phlegmatizers.*

Phlegmatizer (Average molecular formula)	Serezin M75 ($C_{46}H_{94}$)	Wax O ($C_{18}H_{35}NO$)	Ozone Wax ($C_{40}H_{82}$)	Palmowax ($C_{18}H_{76}N_2O_2$)	Wax E ($C_{22}H_{43}NO$)
Assumed molecular formula of the explosive system	$C_{18,53}H_{29,75}N_{17,91}O_{20,42}Al_{6,30}$	$C_{18,03}H_{28,28}N_{18,16}O_{20,67}Al_{6,30}$	$C_{18,53}H_{29,77}N_{17,91}O_{20,42}Al_{6,30}$	$C_{17,13}H_{34,66}N_{18,30}O_{20,81}Al_{6,30}$	$C_{18,53}H_{29,77}N_{17,91}O_{20,42}Al_{6,30}$
Oxygen balance	-65,55	-62,38	-65,56	-64,35	-62,89
Main detonation products (mol/kg)	CO: 18,01; H_2: 14,44; N_2:6,76; AlN: 3,96; Al_2O_3: 0,65; Al: 0,11; H 0,20; Al_2O: 0,43; HCN: 0,41; AlH: 0,06...	CO: 17,57; H_2: 13,72; N_2: 7,26; AlN: 3,25; Al_2O_3: 0,82; Al: 0,14; H: 0,23; Al_2O: 0,58; HCN: 0,38; AlH: 0,07...	CO: 18,00; H_2: 14,46; N_2: 6,77; AlN: 3,95; Al_2O_3: 0,65; Al: 0,11; H: 0,20; Al_2O: 0,43; HCN: 0,41; AlH: 0,06...	CO: 16,64; H_2: 16,87; N_2: 7,70; AlN: 2,50; Al_2O_3: 1,17; Al: 0,14; H: 0,26; Al_2O: 1,17; HCN: 0,40; AlH: 0,08...	CO: 17,64; H_2: 13,83; N_2: 7,17; AlN: 3,78; Al_2O_3: 0,80; Al: 0,13; H: 0,22; Al_2O: 0,55; HCN: 0,39; AlH: 0,07...

Table 3. *Calculated heat of explosion of the composite explosive using various phlegmatizers.*

Phlegmatizer	Serezin M75 ($C_{46}H_{94}$)	Wax O ($C_{18}H_{35}NO$)	Ozone Wax ($C_{40}H_{82}$)	Palmowax ($C_{18}H_{76}N_2O_2$)	Wax E ($C_{22}H_{43}NO$)
Calculated heat of explosion (kcal/kg)	1786	1480	1684	1548	1516

Consequently, experimental samples were fabricated utilizing the nominal baseline formulation (57% RDX, 19% TNT, 17% Al, and 7% phlegmatizer) to physically evaluate the resultant detonation characteristics. Furthermore, 0,3% CTAB was added externally (as a weight percentage in excess of 100%) to function as a rheological modifier during the compounding process. The casting density and ballistic properties corresponding to the various phlegmatizers are detailed in Table 4.

Table 4. *Influence of various phlegmatizers on the casting density and detonation characteristics of MC explosive.*

Phlegmatizer	Casting density, g/cm^3	Lead cylinder compression, mm	Work capacity (ballistic pendulum), %TNT	Detonation velocity at 1,7 g/cm^3, m/s	Heat of explosion, kcal/kg	Impact sensitivity, %
Serezin M75	1,688	23,97	135,50	7630	1475	8
Ozone Wax	1,680	23,85	135,31	7493	1433	8
Wax O	1,682	23,68	135,14	7528	1445	8
Palmowax SF	1,681	23,71	135,21	7456	1437	8
Wax E	1,678	23,79	135,32	7481	1381	8

The results in Table 4 indicate that while substituting the five different phlegmatizers does not radically alter the primary ballistic properties of the MC explosive, the formulation utilizing Serezin M75 exhibits demonstrably superior technological properties. This translates to more favorable melt-casting rheology, yielding higher structural density in the cast charge, which in turn maximizes the detonation velocity. Thus, Serezin M75 was selected as the standard phlegmatizer for all subsequent experimental phases.

3.2. Influence of RDX and aluminum powder content on detonation characteristics

To evaluate the impact of constituent ratios on the energetic parameters, various samples were formulated by systematically modifying the mass ratio of RDX to Al powder, while maintaining the other constituents. To enhance the processing rheology and optimize packing density, a trimodal particle size distribution of Al powder was employed, specifically: 25% particles ≤ 5 µm, 60% particles ranging 10-25 µm, and 15% particles ranging 40-80 µm. The empirical results are summarized in Table 5.

***Table 5.** Influence of RDX and Al powder content on the technical characteristics of MC explosive.*

Component/parameter	Result 1	Result 2	Result 3	Result 4	Result 5
TNT content, %	19	19	19	19	19
RDX content, %	53	55	57	59	61
Al content, %	21	19	17	15	13
Serezin M75 content, %	7	7	7	7	7
CTAB (external addition), %	0.3	0.3	0.3	0.3	0.3
Casting density, g/cm³	1,732	1,720	1,711	1,693	1,674
Lead cylinder compression, mm	22,01	22,90	23,97	24,84	25,81
Work capacity (ballistic pendulum), % TNT	128,50	130,71	135,50	136,45	137,50
Detonation velocity at casting density, m/s	7350	7529	7630	7719	7812
Heat of explosion, kcal/kg	1531	1505	1475	1445	1416
Impact sensitivity, %	4	8	8	16	32

The empirical data demonstrate that inversely varying the RDX and Al powder content induces distinct trends. As RDX content increases (and Al decreases), both the charge density and the overall heat of explosion decrease. Conversely, indicators of brisance and impulse-such as lead cylinder compression, ballistic pendulum work capacity, and detonation velocity-exhibit a proportional increase. This corroborates that RDX acts as the primary driver of detonation kinetics (brisance), while Al powder predominantly serves to augment the thermodynamic heat output. Since the average particle size of RDX is substantially larger than that of the metallic Al powder, increasing the mass fraction of coarse RDX particles reduces the maximum theoretical solid packing fraction within the matrix, thereby lowering the bulk casting density. Reversing the ratio naturally increases the structural density due to the superior interstitial filling capabilities of the fine Al powder.

3.3. Influence of TNT and aluminum powder content on detonation characteristics

The research team subsequently varied the mass ratio of TNT to Al powder to investigate their combined effect on the ballistic performance of the composite mixture. The results are outlined in Table 6.

The experimental data indicate that increasing the Al powder content at the expense of the TNT binder initially tends to increase the composite density. However, severely reducing the mass fraction of TNT inherently diminishes the volume of the continuous liquid melt phase. This reduction drastically elevates the viscosity of the slurry, impeding effective mechanical homogenization and making the melt-casting process severely problematic. Consequently, the resulting explosive charges suffer from internal heterogeneity, causing the observed ballistic parameters to deviate unpredictably from theoretical models. The specific formulation containing a TNT : RDX : Al : Phlegmatizer ratio of 19 : 57 : 17 : 7 proved optimal, offering excellent technological flow characteristics, maximum solid loading density, and unhindered manufacturability for munition loading.

Table 6. *Influence of TNT and Al powder content on the technical characteristics of MC explosive.*

Component/parameter	Result 6	Result 7	Result 3	Result 8	Result 9
TNT content, %	23	21	19	17	15
RDX content, %	57	57	57	57	57
Al content, %	13	15	17	19	21
Serezin M75 content, %	7	7	7	7	7
CTAB (external addition), %	0.3	0.3	0.3	0.3	0.3
Casting density, g/cm³	1,674	1,695	1,711	1,689	1,651
Lead cylinder compression, mm	20,12	21,54	23,97	24,02	22,15
Work capacity (ballistic pendulum), % TNT	128,20	130,03	135,50	136,40	129,50
Detonation velocity at casting density, m/s	7742	7691	7630	7572	7364
Heat of explosion, kcal/kg	1432	1456	1475	1438	1374
Impact sensitivity, %	8	8	8	8	16

Correlating the data synthesized across the experimental matrices, it is evident that an optimized formulation of (19 ± 2)% TNT, (57 ± 3)% RDX, (17 ± 2)% Al, and 7% Phlegmatizer guarantees ballistic and energetic specifications equivalent to those of foreign benchmark standards while concurrently satisfying the rigorous rheological demands of industrial-scale melt-casting procedures.

4. CONCLUSIONS

Through systematic investigation, Serezin M75 was successfully identified as the optimal phlegmatizer, providing excellent technological properties that facilitate the melt-casting process to achieve high charge densities. The active components-TNT, RDX, and Al powder-directly govern the detonation characteristics of the resultant MC explosive. For the RDX component, elevating its mass fraction directly enhances the detonation velocity, ballistic pendulum work capacity, and the lead cylinder compression of the composite. Regarding the aluminum powder, increasing its concentration systematically elevates the heat of explosion. Furthermore, substituting Al powder for TNT within calibrated limits can improve specific explosive output metrics (work capacity and lead cylinder compression); however, excessive Al substitution invariably diminishes the detonation velocity. The TNT mass fraction is paramount for ensuring the processability of the composite mixture; reducing TNT below 17% results in an unacceptably high dynamic viscosity, rendering gravity melt-casting unfeasible. Ultimately, a composition comprising (19 ± 2)% TNT, (57 ± 3)% RDX, and (17 ± 2)% Al yields detonation performance equivalent to that of analyzed foreign baseline samples. Notably, the precise formulation of 19 : 57 : 17 : 7 (TNT : RDX : Al : Additives) exhibits the most favorable manufacturing characteristics, reliably permitting loading densities in excess of 1.7 g/cm³.

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TÓM TẮT

Nghiên cứu ảnh hưởng của thành phần đến quá trình chế tạo và đặc trưng xạ thuật của thuốc nổ MC

Bài báo trình bày kết quả nghiên cứu ảnh hưởng của các thành phần đến quá trình chế tạo và đặc trưng xạ thuật của thuốc nổ MC. Kết quả nghiên cứu cho thấy Serezin M75 phù hợp để chế tạo thuốc nổ MC. Các thành phần TNT, RDX, bột nhôm ảnh hưởng trực tiếp đến các đặc tính xạ thuật của thuốc nổ MC. Hàm lượng các chất TNT (19 ± 2)% ; RDX (57 ± 3)% ; Al (17± 2) cho chỉ tiêu xạ thuật của thuốc nổ tương đương với mẫu phân tích của nước ngoài. Trong đó mẫu có thành phần TNT : RDX : Al : CTH = 19 : 57 : 17 : 7 cho đặc tính công nghệ tốt nhất, có thể nhồi nạp được mật độ trên 1,7 g/cm^3.

Từ khóa: Thuốc nổ MC; TNT; RDX; Bột nhôm; Tốc độ nổ; Khả năng sinh công.