

Features and mechanism of combustion of energetic materials based on tungsten and polytetrafluoroethylene

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Abstract: Multifunctional energetic materials (reactive materials) under normal conditions are inert mixtures, but under strong mechanical or thermal impact they are capable of intensive exothermic reactions. For the development of reactive materials and optimization of their composition it is necessary to take into account the sequences of chemical reactions. The features of combustion in powder reactive material based on tungsten, polytetrafluoroethylene and aluminum have been investigated. Since the metal components react with the decomposition products of polytetrafluoroethylene, this stage was studied in separate experiments on combustion of metals with CF₄ tetrafluoromethane. The use of tetrafluoromethane instead of polytetrafluoroethylene made it possible to determine that in the Al–CF₄ system the reaction starts at 900–1000 °C, and in the W–Al system at 700 °C. Intensive evaporation of polytetrafluoroethylene in the W–PTFE–Al system prevents the reaction of tungsten with aluminum, which leads to ignition at 900–1000 °C. Combustion of two-component systems W–Al and Al–CF₄ showed that the heat released during their interaction is insufficient for self-sustaining synthesis. Combustion of W–Al samples in tetrafluoromethane environment is realized in self-sustained mode. The reaction of tungsten with aluminum gives the initial impulse, and the main heat source is the interaction of aluminum with tetrafluoromethane.

Keywords: ignition; combustion; reactive materials; reaction mechanism; energy materials.

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Особенности и механизм горения энергетических материалов на основе вольфрама и политетрафторэтилена

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Аннотация: Многофункциональные энергетические материалы (реакционные материалы) при нормальных условиях являются инертными смесями, а при сильном механическом или тепловом воздействии способны к интенсивной экзотермической реакции. Для разработки реакционных материалов и оптимизации их состава необходимо учитывать последовательности химических реакций. Исследованы особенности горения в порошковом реакционном материале на основе вольфрама, политетрафторэтилена и алюминия. Поскольку металлические компоненты должны вступать в реакцию с продуктами разложения политетрафторэтилена, эта стадия выделена в отдельные эксперименты по горению металлов с тетрафторметаном CF₄. Использование тетрафторметана вместо политетрафторэтилена позволило установить, что в системе Al–CF₄ реакция начинается при 900...1000 °C, а в системе W–Al при 700 °C. Интенсивное испарение политетрафторэтилена в системе W–ПТФЭ–Al препятствует реагированию вольфрама с алюминием, что приводит к воспламенению при 900...1000 °C. Горение двухкомпонентных систем W–Al и Al–CF₄ показало, что выделяющееся при их

взаимодействии тепло недостаточно для самоподдерживающегося синтеза. Горение образцов W–Al в среде тетрафторметана реализуется в самоподдерживающемся режиме. Реакция вольфрама с алюминием дает начальный импульс, а основным источником тепла является взаимодействие алюминия с тетрафторметаном.

Ключевые слова: воспламенение; горение; реакционные материалы; механизм реакции; энергетические материалы.

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1. Introduction

Multifunctional reaction materials (RM) under normal conditions are inert mixtures, but under strong mechanical or thermal impact they are capable of intense exothermic reaction [1]. There are three main types of RMs: thermite [2–4], intermetallic [5–7] and metal-polymer mixtures [8–12]. Metal-polymer RMs typically consist of polytetrafluoroethylene (PTFE) and one or more metals. This is a relatively new class of materials that differs from traditional energetic compositions (pyrotechnic compositions, rocket fuel, explosives) by high energy density and safety under normal conditions. High-velocity impact initiates an intense redox reaction (up to deflagration and explosion), releasing a large amount of thermal energy [13].

PTFE, being a source of strong oxidizers (carbon, fluorine), enables oxidation of metals with a high thermal effect (about $8 \text{ MJ} \cdot \text{kg}^{-1}$ for the Al–PTFE system), which is significantly higher than that of TNT [14, 15]. In addition, PTFE is a technological additive – it improves the compactibility of powder compositions to a virtually pore-free state and acts as a protector from external influences (moisture, atmosphere). A metal-polymer mixture can combine sufficient strength, electrical and thermal conductivity of metal with high antifriction properties and chemical resistance of PTFE [16].

Despite its obvious advantages, Al–PTFE RM pressed from powders and sintered has low density and strength [17]. To improve the characteristics of RM, high-density additives in the form of tungsten, nickel, etc. powder are used [16, 18]. In [18], it was shown that with an increase in the content of tungsten or nickel in the Al–PTFE mixture, the strength and density of the composite increases, however, this leads to a decrease in the thermal effect of the reaction and sensitivity to impact initiation.

In addition, an urgent task is to increase the completeness of the reaction: during combustion of RM based on PTFE and high-density additives (W, Hf), the products contain a significant amount of unreacted metal.

A promising RM is a composition based on tungsten and PTFE. Calculations show that the

optimal composition is a mixture with a tungsten content of 80 and 20 wt. % PTFE, which demonstrates a high combustion temperature (2115°C) and a share of condensed products [19]. The main calculated products of this composition are condensed tungsten carbide W_2C (53 wt. %) and graphite (3 wt. %), as well as gaseous tungsten fluorides WF_6 (14 wt. %), WF_5 (20 wt. %), WF_4 (9 wt. %). However, experiments have shown that binary W-PTFE systems are difficult to initiate by shock-wave loading and activating additives are required to increase the reactivity. Such an additive can be aluminum powder, which allows increasing the reactivity of difficult-to-initiate RMs [20, 21]. The completeness of the reaction and the level of energy release of such multicomponent RMs are difficult to predict; they depend heavily, among other things, on the initiation method (heating, impact).

Thus, to develop energy compositions and optimize their composition, it is necessary to take into account the sequences of chemical reactions. Since combustion is a chemical process, it is necessary to take into account the chain nature of PTFE combustion: thermal destruction occurs with a fast stage of chain decomposition of the polymer into monomer links [22]. Therefore, for further improvement of the compositions of new reaction mixtures, an integrated approach to solving the problem is required: the use of specific patterns of chain processes that contribute to an increase in the efficiency of additives. Since the metal components of the RM must react with the decomposition products of PTFE, this stage can be separated into separate experiments on the combustion of metals with the final product of PTFE decomposition – tetrafluoromethane CF_4 (TFM). The aim of the paper is to study the features of combustion and the reaction mechanism in RM based on tungsten and PTFE.

2. Materials and Methods

As a result of the calculation in the ISMAN-THERMO program [23], a powder mixture based on tungsten, PTFE, and aluminum with sufficient exothermic effect and forming solid end products

with high specific gravity was taken as an object of study (Table 1). The maximum adiabatic combustion temperature (T_{ad}) of 2866 °C corresponds to the composition with 10 wt. % Al with a high proportion of condensed products.

The initial components for RMs were tungsten powders PV-2 (particle size ≤ 50 μm), polytetrafluoroethylene Fluralite (≤ 5 μm) and aluminum ASD-1 (≤ 50 μm). Dry mixing of the powders was carried out in a “drunken barrel” mixer for 3 hours with a drum rotation speed of 30 rpm with a ball to powder mass ratio of 5 : 1.

To measure the combustion rate, parallelepiped-shaped samples with dimensions of 5×5×20 mm and a relative density of 0.7–0.8 were prepared using a manual hydraulic press (PGR-10, Lab Tools, St. Petersburg, Russia). Two blind holes with a diameter of 1 mm and a depth of 2 mm were drilled on the side surface of the samples for thermocouples (BP5/20 with a diameter of 100 μm), the distance between the holes was 14–15 mm (Fig. 1a). The samples were installed in a 20-liter reactor [24].

Air was pumped out of the reactor to a value of 2×10^4 Pa, and then either an inert gas (argon) or tetrafluoromethane (CF_4) was pumped in. The sample was initiated from the side end with a graphite plate by passing an electric current (Fig. 1b). The distance from the initiation point to the first thermocouple was about 3–4 mm. Signals from thermocouples were recorded at a frequency of 250 Hz via a QMBox analog-to-digital converter (R-Technology, Moscow, Russia). The X-ray phase analysis (XPA) was performed using DRON-3M. Samples were scanned in the range from 20° to 80° (2 θ) with a step of 0.02°. The quantitative analysis was performed using the corundum number method.

The ignition temperature was measured using the method described in [25, 26] on samples with a diameter of 5 mm and a height of 1.5–2.0 mm. The samples were ignited in a reactor (Fig. 2). The samples were placed on a 50 μm thick VR5/20 thermocouple in a boron nitride crucible and heated at a rate of 70–100 °C·s^{−1} using a graphite plate to achieve thermal explosion conditions.

Table 1. Calculated adiabatic combustion temperature and fraction of condensed products of W-PTFE-Al

Composition, wt. %	T_{ad} , °C	Condensed product, wt. %	Gas product, wt. %
76W-19PTFE-5Al	2776	C – 1 W ₂ C – 77	AlF ₃ – 16; C ₂ F ₂ – 1 CF ₂ – 1; WF ₄ – 3 WF ₅ – 1
72W-18PTFE-10Al	2866	C – 2 W ₂ C – 74	AlF – 7; AlF ₂ – 5 AlF ₃ – 11
64W-16PTFE-20Al	1710	W ₂ C – 66 Al ₄ C ₃ – 4	AlF – 29
56W-14PTFE-30Al	1382	AlF – 23	W ₂ C – 57

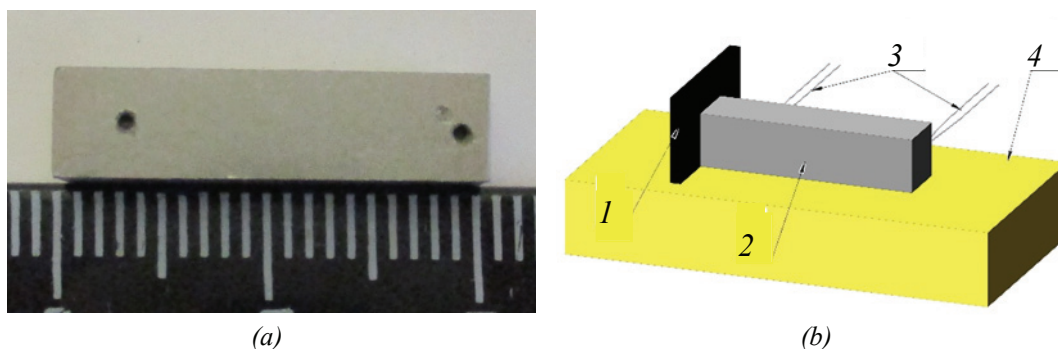


Fig. 1. Combustion rate measurement: a) sample; b) combustion rate measurement scheme: 1 – graphite heater, 2 – sample, 3 – thermocouples BP5/20, 4 – refractory substrate

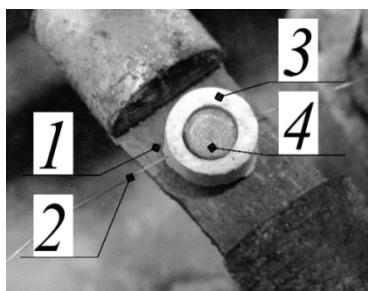
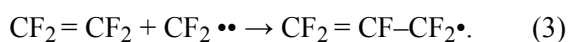
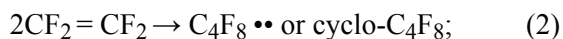


Fig. 2. Measurement of the ignition temperature:
1 – graphite heater; 2 – thermocouple;
3 – boron nitride crucible; 4 – sample

3. Results and Discussion

Under normal conditions, PTFE is inert because the chain of carbon atoms is surrounded by fluorine atoms, which block access to possible oxidants. However, when PTFE $-(CF_2-CF_2)_n-$ is heated, thermal degradation of the polymer occurs, which begins with free-radical initiation. This process is followed by a rapid stage of chain rupture into monomer units from the free-radical end of the polymer chain. Thus, the rupture of the polymer chain leads to the formation of a large number of different free radicals. The main one is $(R-CF_2)-$ difluorocarbene radical [22].



The final product of PTFE decomposition is the monomer tetrafluoroethylene (TFE):

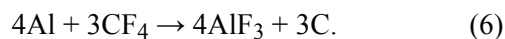


Since the system is constantly heated, TFE also undergoes decomposition. The final products of TFE

decomposition are carbon and tetrafluoromethane CF_4 [27]:



Thus, aluminum and tungsten react with the decomposition products of PTFE:



With excess W content:



The results of calculating the adiabatic combustion temperature and the proportion of products formed when replacing PTFE with TFM showed that the $W-CF_4$ composition behaves similarly to W -PTFE and demonstrates a relatively low combustion temperature (1464 °C) (Table 2). The main calculated products of this composition are condensed tungsten carbides, as well as gaseous tungsten fluorides (Table 2). The calculations showed that an increase in the aluminum content leads to a sharp decrease in the adiabatic combustion temperature (Fig. 3).

Ignition in the $W-CF_4$ -Al-based system began with the melting of aluminum and its interaction with tungsten to a temperature of 1200–1300 °C, regardless of the aluminum content (Fig. 4a). Then, a drop in temperature to 1100–1150 °C was recorded. A further increase in temperature to 1200–1400 °C was associated with the combustion of aluminum with TFM. An increase in the aluminum content increased the rate and duration of the reaction. Ignition of the W -PTFE-Al system began at a temperature of 800–1000 °C, since at this temperature intense evaporation of PTFE and the formation of TFM, which interacted with aluminum, begin (Fig. 4b).

Table 2. Calculated values of the adiabatic combustion temperature and the proportion of condensed products of the $W-CF_4$ -Al

Composition, wt. %	T_{ad} , °C	Condensed product, wt. %	Gas product, wt. %
80W–20CF ₄ –0Al	1464	WC – 32; W ₂ C – 23	WF ₅ – 3; WF ₆ – 41
76W–19CF ₄ –5Al	2416	W ₂ C – 67	AlF ₃ – 16; WF ₄ – 8; WF ₅ – 7; WF ₆ – 1
72W–18CF ₄ –10Al	2777	W ₂ C – 74	AlF – 5; AlF ₂ – 5 AlF ₃ – 16
68W–17CF ₄ –15Al	1777	W ₂ C – 70	AlF – 20; AlF ₂ – 2 AlF ₃ – 8
64W–16 CF ₄ –20Al	1277	W ₂ C – 66; Al – 4	AlF – 24; AlF ₃ – 5

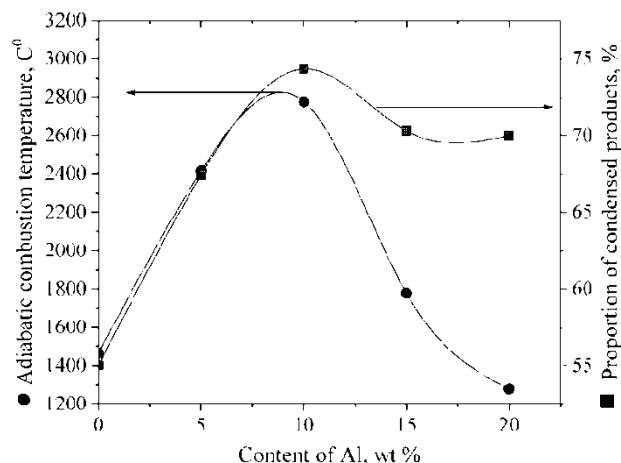
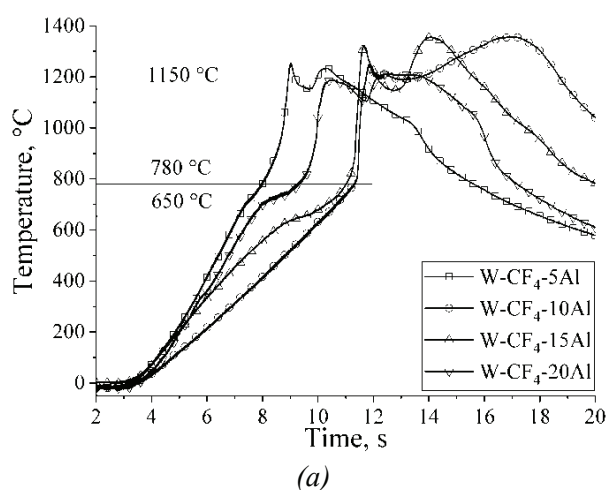


Fig. 3. The adiabatic combustion temperature and the proportion of condensed products in the W-CF₄-Al system depending on the aluminum content

According to the thermograms of the studied mixtures, it is evident that when PTFE is replaced by TFM, the combustion intensity increases (Fig. 4a).



This is manifested in an increase in the slopes and height of the peaks of the curves, as well as in a decrease in the ignition temperature. The lower intensity of ignition of the mixture with PTFE is associated with the process of polymer decomposition and the removal of decomposition products from the reaction zone.

To confirm the above mechanisms and the role of TFM in increasing the ignition intensity, tungsten and aluminum were heated both together and separately (Fig. 5a). When tungsten was heated in TFM, ignition did not occur, and the temperature increased only due to continuous heating. When aluminum was heated in TFM, ignition began at a temperature of 900 °C and reached 1300 °C, and then the temperature dropped to 1100 °C with a subsequent increase to 1300 °C. The main ignition products in the Al-CF₄ system were AlF₃ and Al₄C₃ (Fig. 5b). The Al-W and Al-W-CF₄ systems ignited at 600–700 °C when heated.

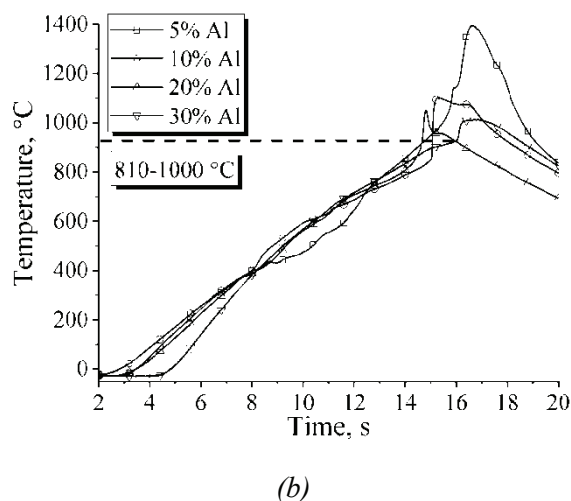


Fig. 4. Thermograms of ignition of system samples: a) W-CF₄-Al, b) W-PTFE-Al

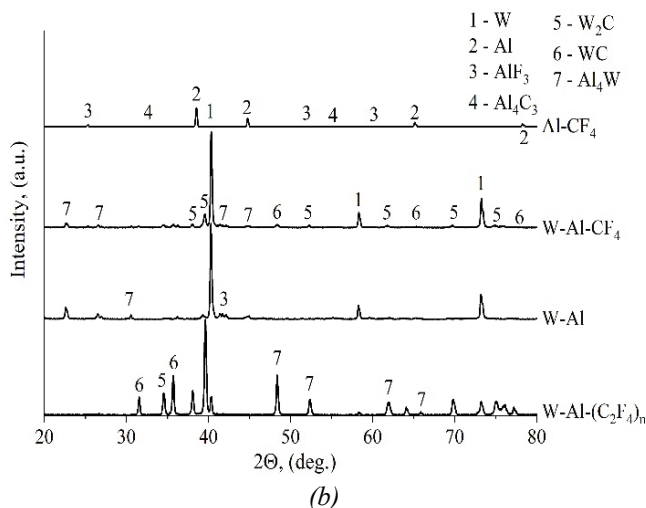
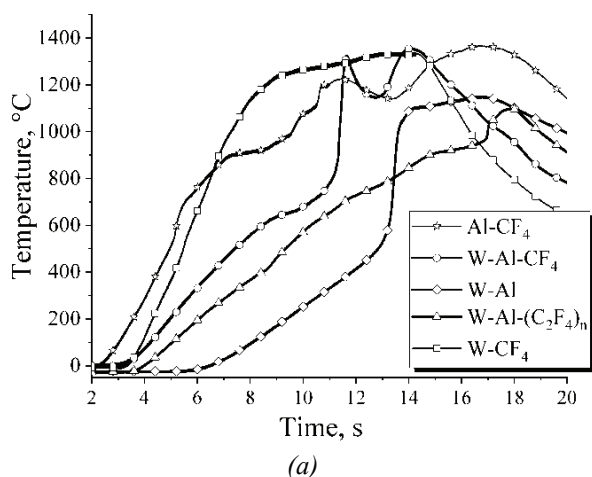


Fig. 5. a) Thermograms of ignition of samples, b) XRD of combusted samples

The main product in the mixture without TFM was the intermetallic Al_4W , and when TFM was used, tungsten carbides were formed (Fig. 5b). The conducted ignition experiments show that the intense evaporation of PTFE in the W-PTFE-Al system prevents the interaction of tungsten with aluminum. Thus, the interaction of aluminum with TFM provides enough heat to form tungsten carbides and aluminides.

The experimental results showed that the Al- CF_4 , 72 wt. % W – 10 wt. % Al systems are capable of ignition when heated, unlike W- CF_4 (Fig. 6a). As can be seen from the thermograms, the reactions of tungsten with aluminum and aluminum with TFM do not occur in a self-sustaining mode. High temperatures are not required for ignition of the W-Al system, but due to the low exothermicity of this reaction, the synthesis is not realized in a self-sustaining mode. To implement the self-sustaining mode in the Al- CF_4 system, a temperature significantly exceeding the melting point of aluminum is required; such conditions are created only near the heating element.

The experimental results on combustion of the system based on W- CF_4 -Al with different aluminum content show the possibility of implementing a self-sustaining reaction with the participation of three components (Fig. 6b). The reaction was initiated by the interaction of tungsten with aluminum, and the self-sustaining synthesis mode occurs due to the reaction of aluminum with TFM with a combustion temperature of about 1200–1300 °C (Fig. 6a). The combustion rate is minimal for the composition with 5 wt. % Al – about 0.3 mm·s⁻¹. The maximum combustion rate for the composition with 20 wt. % Al was 1.4 mm·s⁻¹, while for the compositions with 10 and 15 wt. % Al they were 0.5 and 0.6 mm·s⁻¹, respectively.

The sample of the W- CF_4 -Al system with a content of 5 wt. % Al combusted partially, and the unreacted part showed tarnish colors (Fig. 7a). The samples with a content of 10, 15, and 20 wt. % Al combusted completely, forming a white coating on the surface, and the samples elongated from 20 to 30 mm (Fig. 7b).

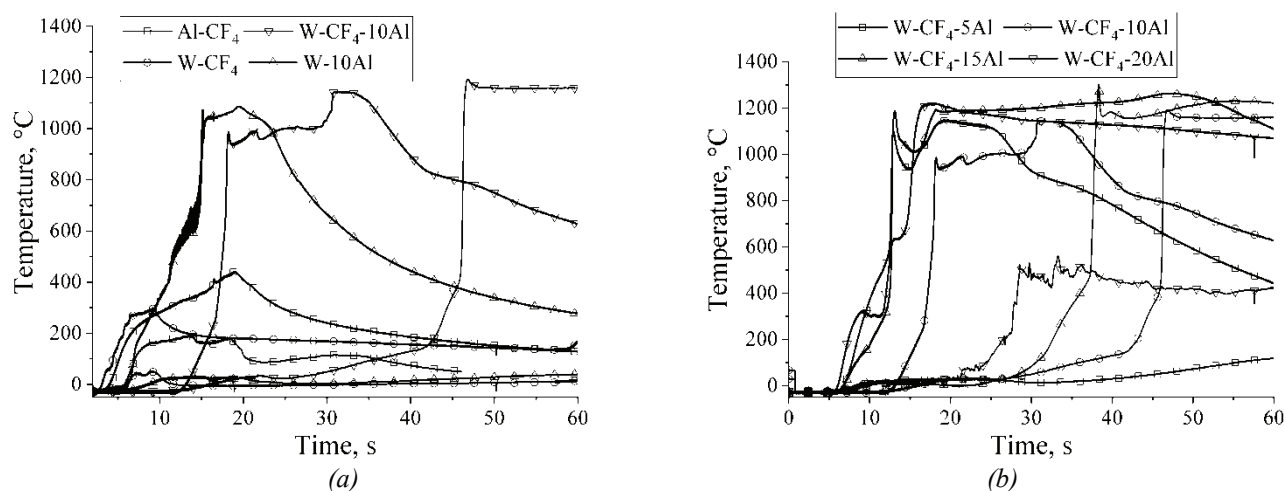


Fig. 6. Combustion thermograms of the system: a) W- CF_4 , Al- CF_4 , W-10Al, W- CF_4 -10Al; b) W- CF_4 -5/10/15/20Al

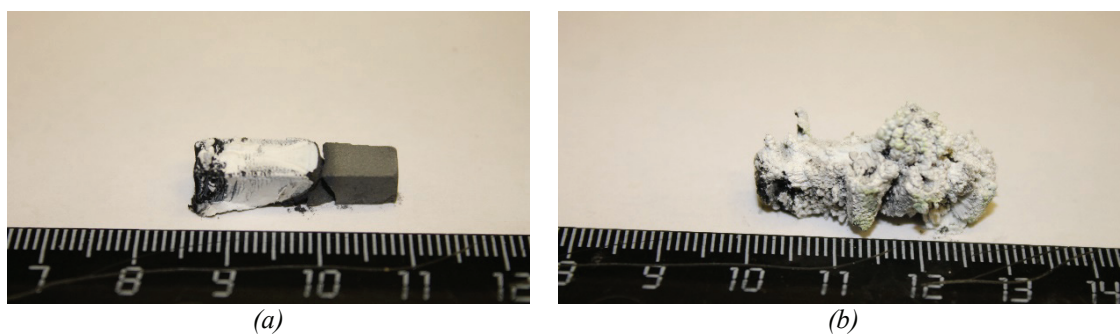


Fig. 7. Samples after combustion W- CF_4 -Al: a) 5 % Al, b) 20 % Al

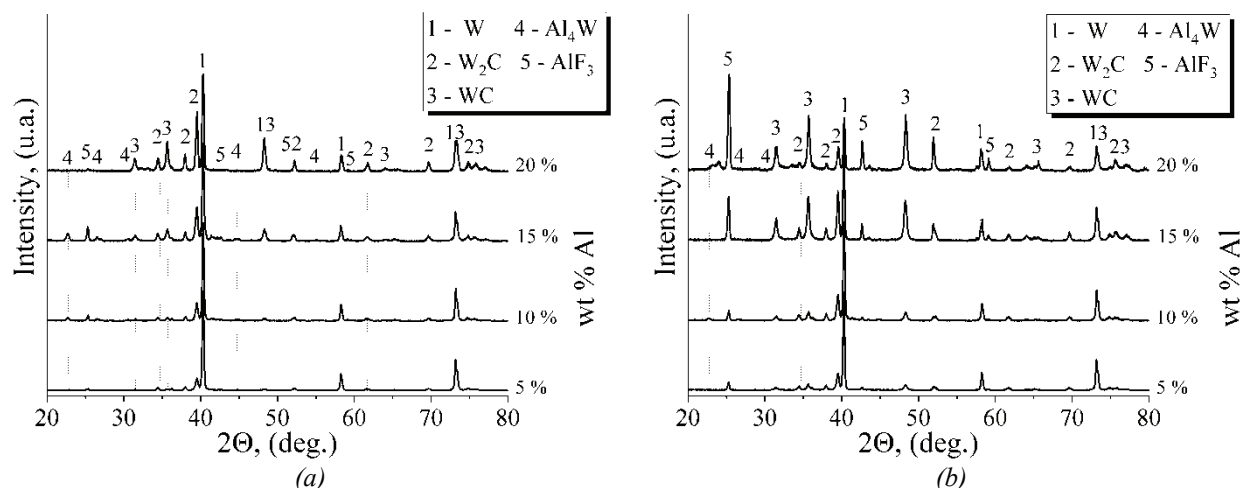


Fig. 8. XRD of the inner (a) and outer (b) parts of the W-CF₄-Al samples separately

Table 3. Quantitative analysis of combustion products of the W-CF₄-Al system

Sample	Phase content, wt. %				
	W Cubic Im-3m	W ₂ C Hexagonal P-31m	WC Hexagonal P-6m2	AlF ₃ Rhomboidal R-3c	Al ₄ W Monoclinic Cm
5 % Al outer	57	16	5	23	—
5 % Al inner	79	16	1	4	—
10 % Al outer	46	20	4	23	7
10 % Al inner	55	16	2	15	12
15 % Al outer	22	18	12	48	—
15 % Al inner	34	20	4	25	17
20 % Al outer	8	6	10	75	—
20 % Al inner	40	40	15	5	—

Due to the nature of combustion of the samples, X-ray fluorescence analysis was carried out separately for their external and internal parts (Fig. 8). Based on the intensity of the peaks of the formed products, it can be concluded that increasing the aluminum content reduces the amount of unreacted components both outside and inside the sample (Fig. 8).

The quantitative analysis of the outer part of the sample showed that an increase in the aluminum content leads to an increase in the proportion of AlF₃ from 5 to 75 wt. %. The proportion of WC increased from 4–5 to 10–12 wt. %, and the proportion of W₂C in the compositions with 5, 10 and 15 wt. % Al was from 16 to 20 wt. %. In the composition with 20 wt. % Al, the proportion of W₂C decreased to 6 wt. %. The quantitative analysis of the inner part of the sample shows that at 5 and 20 wt. % Al, the proportion of AlF₃ was about 5 wt. %. This fact indicates that aluminum fluoride is formed mainly on

the surface of the sample. An increase in the Al content in the sample leads to an increase in the formation of Al₄W, WC and W₂C to 17, 15 and 40 wt. %, respectively. As expected, the proportion of unreacted components is higher inside the sample (Table 3).

4. Conclusion

The combustion features and reaction mechanism in a reactive material based on tungsten with aluminum and polytetrafluoroethylene are investigated. At high temperatures, PTFE decomposes by a radical-chain mechanism, where the main decomposition product is the tetrafluoroethylene monomer. With further heating of tetrafluoroethylene, it decomposes to carbon and TFM. When PTFE is replaced by TFM, the ignition of the W-CF₄-Al system begins with the interaction of tungsten with aluminum at 700 °C with a temperature increase to

1300 °C, and at 900–1100 °C, aluminum burns in TFM with an increase to 1300 °C. In the W–PTFE–Al system, ignition begins only at 900 °C due to intense evaporation of PTFE and loosening of the sample, which prevents the interaction of tungsten with aluminum.

Combustion of two-component W–Al and Al–CF₄ systems showed that the heat released during their interaction is insufficient for self-sustaining synthesis. Combustion of W–Al samples in the TFM environment is realized in a self-sustaining mode. The reaction of tungsten with aluminum gives the initial impulse, and the main source of heat is the combustion of aluminum in the TFM, which provides conditions for the formation of tungsten carbides. Increasing the aluminum content in the W–CF₄–Al system increases the completeness of synthesis and the combustion rate from 0.3 to 1.4 mm·s⁻¹.

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6. Conflict of interests

The authors declare no conflict of interests.

References

1. Zhang H, Wang H, Ge C. Characterization of the dynamic response and constitutive behavior of PTFE/Al/W reactive materials. *Propellants, Explosives, Pyrotechnics*. 2020;45(5):788-797. DOI:10.1002/prep.201900334
2. Glavier L, Taton G, Duc  r   J-M, Baijot V, et al. Nanoenergetics as pressure generator for nontoxic impact primers: comparison of Al/Bi₂O₃, Al/CuO, Al/MoO₃ nanothermites and Al/PTFE. *Combustion and Flame*. 2015;162(5):1813-1820. DOI:10.1016/j.combustflame.2014.12.002
3. Bacciochini A, Radulescu MI, Yandouzi M, Maines G, et al. Reactive structural materials consolidated by cold spray: Al–CuO thermite. *Surface and Coatings Technology*. 2013;226:60-67. DOI:10.1016/j.surfcoat.2013.03.036
4. Wang H, Jian G, Egan GC, Zachariah MR. Assembly and reactive properties of Al/CuO based nanothermite microparticles. *Combustion and Flame*. 2014;161(8):2203-2208. DOI:10.1016/j.combustflame.2014.02.003
5. He W, Liu P, He G, Gozin M, et al. Highly reactive metastable intermixed composites (MICs): preparation and characterization. *Advanced Materials*. 2018;30(41):1706293. DOI:10.1002/adma.201706293
6. Li J, Li W, Wang X. Effects of shock stress and microstructure on shock response of Al–Hf reactive materials. *Journal of Alloys and Compounds*. 2024;970:172569. DOI:10.1016/j.jallcom.2023.172569
7. Tu J, Qiao L, Shan Y, Xin C, et al. Study on the impact-induced energy release characteristics of Zr_{68.5}Cu₁₂Ni₁₂Al_{7.5} amorphous alloy. *Materials*. 2021;14(6):1447. DOI:10.3390/ma14061447
8. Cai Y, Feng X, He C, Zhang S, et al. A 7.62 mm energetic bullet filled with PTFE–Mg-based reactive materials for anti-drone application. *Journal of Materials Research and Technology*. 2024;30:8749-8759. DOI:10.1016/j.jmrt.2024.05.240
9. Wu J, Fang X, Gao Z, Wang H, et al. Investigation on mechanical properties and reaction characteristics of Al–PTFE composites with different Al particle size. *Advances in Materials Science and Engineering*. 2018;2018(1):2767563. DOI:10.1155/2018/2767563
10. Zhang X-B, Liu J-X, Wang L, Li S-K. Reaction mechanism, insensitivity and mechanical property of PTFE–Mg–W composites with magnesium particles surface modification. *Rare Metals*. 2023;42(2):688-696. DOI:10.1007/s12598-017-0962-1
11. Zhuang Z, Xu K, Liu B, Shi Y, et al. Improved reactivity and energy release performance of core-shell structured fuel-rich Si/PTFE energetic composites. *Combustion and Flame*. 2023;255:112889. DOI:10.1016/j.combustflame.2023.112889
12. Feng B, Qiu C, Zhang T, Hu Y, et al. Sensitivity of Al–PTFE upon low-speed impact. *Propellants, Explosives, Pyrotechnics*. 2019;44(5):630-636. DOI:10.1002/prep.201800335
13. Zhang Z, He Y, He Y, Guo L, et al. Compressive mechanical properties and shock-induced reaction behavior of Zr/PTFE and Ti/PTFE Reactive Materials. *Materials*. 2022;15(19):6524. DOI:10.3390/ma15196524
14. Wang L, Liu J, Li S, Zhang X. Investigation on reaction energy, mechanical behavior and impact insensitivity of W–PTFE–Al composites with different W percentage. *Materials & Design*. 2016;92:397-404. DOI:10.1016/j.matdes.2015.12.045
15. Li Y, Ou Y, Wu J, Zhang Y. Modeling and simulation of laser-ignited Al–PTFE reactive material in vacuum. *Case Studies in Thermal Engineering*. 2024;61:104827. DOI:10.1016/j.csite.2024.104827
16. Adamenko NA, Kazurov AV, Agafonova GV, Savin DV. Structure formation in nickel-polytetrafluoroethylene composite materials upon explosive pressing of powders. *Inorganic Materials: Applied Research*. 2020;11(4):982-990. DOI:10.1134/S2075113320040036
17. Hastings DL, Dreizin EL. Reactive structural materials: preparation and characterization. *Advanced Engineering Materials*. 2018;20(3):1700631. DOI:10.1002/adem.201700631
18. Wu J, Wang H, Fang X, Li Y, et al. Investigation on the thermal behavior, mechanical properties and reaction characteristics of Al–PTFE composites enhanced by Ni particle. *Materials*. 2018;11(9):1741. DOI:10.3390/ma11091741

19. Yu ZS, Fang X, Gao ZR, Wang HX, et al. Mechanical and reaction properties of Al/TiH₂/PTFE underquasi-static compression. *Advanced Engineering Materials*. 2018;20(7):1800019. DOI:10.1002/adem.201800019

20. Alymov MI, Vadchenko SG, Saikov IV, Kovalev ID. Shock-wave treatment of tungsten/fluoropolymer powder compositions. *Inorganic Materials: Applied Research*. 2017;8(2):340-343. DOI:10.1134/S2075113317020022

21. Saikov I, Seropyan S, Malakhov A, Saikova G, et al. Energetic materials based on W/PTFE/Al: thermal and shock-wave initiation of exothermic reactions. *Metals*. 2021;11(9):1355. DOI:10.3390/met11091355

22. Madorsky SL. *Thermal degradation of organic polymers*. New York: Interscience Publishers; 1964. 348 p.

23. Shiriev AA, Mukasyan AS. Thermodynamics of SHS processes. *Concise Encyclopedia of Self-Propagating High-Temperature Synthesis*. New York: Elsevier; 2017. p. 385-387.

24. Seropyan S, Saikov I, Andreev D, Saikova G, et al. Reactive Ni–Al-based materials: strength and combustion behavior. *Metals*. 2021;11(6):949. DOI:10.3390/met11060949

25. Vadchenko SG, Alymov MI, Saikov IV. Ignition of some powder mixtures of metals with teflon. *Inorganic Materials: Applied Research*. 2018;9(3):517-522. DOI:10.1134/S2075113318030309

26. Alymov MI, Vadchenko SG, Gordopolova IS. Ignition and combustion of W–Teflon–Al mixtures. *Izvestiya vysshikh uchebnykh zavedeniy. Poroshkovaya metallurgiya i funktsional'nye pokrytiya*. 2018;2:54-60. DOI:10.17073/1997-308X-2018-2-54-60 (In Russ.)

27. Archer G, Hildebrand JH. The solubility and entropy of solution of carbon tetrafluoride and sulfur hexafluoride in nonpolar solvents. *Journal of Physical Chemistry*. 1963;67(9):1830-1833. DOI:10.1021/j100803a021

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