Journal of Advanced Materials and Technologies. 2026. Vol. 11, No. 1

Original papers
Nanostructured, nanoscale materials and nanodevices

УДК 621.762.4 DOI: 10.17277/jamt-2026-11-01-081-089

Shock-wave loading of W–PTFE–Al reaction materials based on nanoscale tungsten in cylindrical recovery ampoules

© Ivan V. Saikov[a], Stepan A. Seropyan[a]✉, Denis V. Shakhray[b],
Alexandr V. Smirnov[a], Gulnaz R. Saikova[a]

[a] *Merzhanov Institute of Structural Macrokinetics and Materials Science RAS,*
8, Academician Osipyan St., Chernogolovka, 142432, Russian Federation,
[b] *Federal Research Center of Problems of Chemical Physics and Medicinal Chemistry RAS,*
1, Academician Semenova Av., Chernogolovka, 142432, Russian Federation

✉ stepan.seropyan@yandex.ru

Abstract. The effect of nanosized tungsten on the ignition of W–PTFE–Al compositions under shock-wave or thermal impact has been investigated. It has been found that ignition in the studied compositions occurs at 1000–1060 °C with rapid temperature increase to 1700 °C. The mechanism and localization of synthesis in the studied compositions under shock-wave loading in recovery ampoules depends on aluminum content. Compositions with low aluminum content (5–10 wt. %) ignite in low-pressure regions (upper part of the ampoule), whereas those with high Al content (20–30 wt. %) ignite in high-pressure regions (lower part of the ampoule). The 72W–18PTFE–10Al composition demonstrated the highest energy release, causing nearly complete ampoule destruction (70 % of length). The use of nanosized tungsten enabled shock-wave synthesis initiation in the 56W–14PTFE–30Al composition and revealed structural changes along the sample length. Following shock-wave loading of 64W–16PTFE–20Al and 56W–14PTFE–30Al compositions, the synthesized products underwent dispersion under atmospheric moisture exposure without phase composition changes.

Keywords: shock-wave loading; W–PTFE–Al; nanoparticles; reactive materials; combustion explosion.

For citation: Saikov IV, Seropyan SA, Shakhray DV, Smirnov AV, Saikova GR. Shock-wave loading of W–PTFE–Al reaction materials based on nanoscale tungsten in cylindrical recovery ampoules. *Journal of Advanced Materials and Technologies*. 2026;11(1):081-089. DOI: 10.17277/jamt-2026-11-01-081-089

Ударно-волновое нагружение реакционных материалов системы W–ПТФЭ–Al на основе наноразмерного вольфрама в цилиндрических ампулах сохранения

© И. В. Сайков[a], С. А. Серопян[a]✉, Д. В. Шахрай[b], А. В. Смирнов[a], Г. Р. Сайкова[a]

[a] *Институт структурной макрокинетики и проблем материаловедения им. А. Г. Мержанова РАН,*
ул. Академика Осипьяна, 8, Черноголовка, 142432, Российская Федерация,
[b] *Федеральный исследовательский центр проблем химической физики и медицинской химии РАН,*
пр. Академика Семенова, 1, Черноголовка, 142432, Российская Федерация

✉ stepan.seropyan@yandex.ru

Аннотация. Исследовано влияние нанодисперсного вольфрама на инициирование горения составов системы W–ПТФЭ–Al при ударно-волновом или тепловом воздействии. Установлено, что воспламенение в исследуемых составах инициируется при 1000…1060 °С с интенсивным ростом температуры до 1700 °С. Механизм и локализация синтеза при ударно-волновом нагружении исследуемых составов в ампулах сохранения зависит от содержания алюминия. Составы с низким содержанием алюминия (5–10 мас. %) инициируются в области с низким давлением (в верхней части ампулы), тогда как составы с высоким содержанием Al (20–30 мас. %) в области с высоким давлением (в нижней части ампулы). Состав 72W–18ПТФЭ–10Al продемонстрировал наибольшее энерговыделение, так как привел к почти полному разрушению ампулы (70 % длины). Использование нанодисперсного вольфрама позволило инициировать синтез ударно-волновым нагружением в составе 56W–14ПТФЭ–30Al и установить изменение структуры по длине образца. В результате ударно-волнового нагружения составов 64W–16ПТФЭ–20Al и 56W–14ПТФЭ–30Al полученные продукты синтеза подвержены диспергированию под действием атмосферной влаги без изменения фазового состава.

Ключевые слова: ударно-волновое нагружение; W–ПТФЭ–Al; наночастицы; реакционные материалы; тепловой взрыв.

Для цитирования: Saikov IV, Seropyan SA, Shakhray DV, Smirnov AV, Saikova GR. Shock-wave loading of W–PTFE–Al reaction materials based on nanoscale tungsten in cylindrical recovery ampoules. *Journal of Advanced Materials and Technologies*. 2026;11(1):081-089. DOI: 10.17277/jamt-2026-11-01-081-089

1. Introduction

The synthesis of functional materials using shock-wave loading (SWL), particularly with preservation ampoules, is a promising research direction [1–4]. A preservation ampoule is a container for holding the test powdered material, intended for subsequent processing with intense shock waves and preservation of the resulting sample for further analysis. This method provides short-term exposure (on the order of microseconds, 10^{-6} s) to the material, creating extreme pressures and temperatures within it [5–11]. During this time interval, under plastic deformation and interparticle friction, the surface of the powder particles becomes activated, accompanied by the destruction of oxide films. As a result, a strong metallic framework forms, and adhesion at interphase boundaries is enhanced, ultimately enabling the production of composites with improved physico-mechanical properties (strength, density, corrosion resistance, and friction coefficient) [5–8]. One of the key features of SWL is its ability to initiate exothermic chemical reactions in materials [12, 13]. Thus, in reactive systems, such as aluminum with polytetrafluoroethylene (Al–PTFE), shock-wave impact can trigger intense heat release, potentially leading to the initiation of a self-propagating high-temperature synthesis mode and subsequent destruction of the preservation ampoule [11, 14].

Reactive materials (RM) include powder compositions that are inert under normal conditions but capable of intense exothermic reactions when initiated by thermal or shock-wave impulses [1, 4]. This category encompasses compositions for self-propagating high-temperature synthesis (SHS) [13], thermite [4], metallic [15], and metal-polymer systems [4]. Among them, metal-polymer compositions, particularly aluminum with polytetrafluoroethylene (Al–PTFE), attract special interest. This composition exhibits a unique set of properties, such as high sensitivity to shock-wave impact, high gas release, and high specific mass energy (up to 8.5 $\mathrm{MJ \cdot kg^{-1}}$), which is more than twice the energy of TNT [15]. PTFE in this system serves as a source of oxidizers (fluorine, carbon), plasticizer, and protective barrier against atmospheric influences. The combination of metallic and polymeric phases in the composite allows merging the advantages of both components: the strength, electrical and thermal conductivity of aluminum with the low friction, chemical resistance, and processability of the polymer [5]. This makes the Al–PTFE system promising for creating RM based on it.

Despite the advantages of the Al–PTFE system, its practical application is limited by low density and insufficient strength [4]. To address these issues, the composition is modified with high-density metallic additives such as tungsten, nickel, etc. [14, 17]. The study [17] demonstrates that the introduction of these additives significantly enhances the composite's strength characteristics. However, a negative trend is observed: increasing the concentration of strengthening additives leads to a decrease in the overall heat release of the reaction and sensitivity to shock-wave loading, due to the reduced proportion of energetically active components (Al and PTFE) in the mixture. One approach to enhancing the reactivity of high-density additives is increasing the particle dispersion [18].

Special preservation ampoules with cylindrical or flat shapes are used for experimental studies of reactive materials by shock-wave loading [8–10]. The choice of ampoule configuration is determined by the required loading mode, as different pressure and deformation gradients form in the center and periphery of the sample, leading to heterogeneity in the properties of the synthesized material [5]. Thus, the geometry of the preservation ampoule is a key parameter determining the spatial distribution of the composite properties after SWL.

The aim of this paper is to study the dependence of the W–PTFE–Al system sensitivity to shock-wave loading in cylindrical preservation ampoules on the dispersion of the tungsten used.

2. Materials and Methods

2.1. Preparation of raw materials and thermal explosion techniques

For the preparation of reactive materials of the W–PTFE–Al system, powders of nanoscale tungsten (≤ 500 nm), polytetrafluoroethylene (PTFE) of the fluralit grade (≤ 5 μm), and aluminum of the ASD-1 grade (≤ 50 μm) were used. Prior to use, all powders were subjected to moisture removal in a drying oven at a temperature of 150 °C for 12 hours. Powder mixing was carried out in a gravitational mixer for 3 hours. The drum rotation speed was 30 rpm, and the ratio of the mass of grinding media to the mass of the powder mixture was 5:1.

The ignition temperature of the compositions under study was determined by the thermal explosion method [19]. For this purpose, cylindrical samples with a diameter of 3 mm and height of 1.4–1.7 mm were used. The sample was placed in a boron nitride crucible, which was installed directly on the junction of a WR5/20 type thermocouple with a thickness of 50 μm. The crucible with the sample and thermocouple was placed on a graphite heater. The heating rate of the samples was 60–80 $°C \cdot s^{-1}$. Experiments were conducted in a reactor with an inert argon atmosphere (purity ≥ 99.998 %).

Shock-wave impact on the compositions under study was carried out using cylindrical preservation ampoules. Structurally, the ampoule was a steel cylinder 100 mm high with an outer diameter of 16 mm. Both ends of the cylinder had threads for fixing the conical upper and flat lower plugs. Eight cylindrical samples with a diameter and height of 10 mm, pre-pressed to a relative density of 0.97–0.99, were placed inside the ampoule.

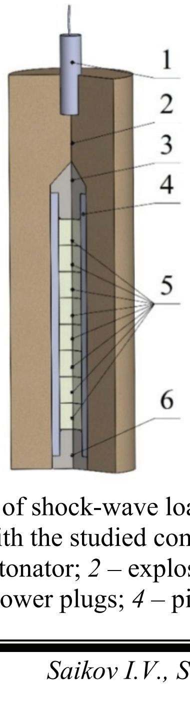


Fig. 1. The scheme of shock-wave loading of recovery ampoules with the studied compositions: *1* – detonator; *2* – explosive; *3*, *6* – upper and lower plugs; *4* – pipe; *5* – samples

The use of eight samples ensures dense filling of the internal volume of the ampoule, allowing for uniform material density throughout the height. The gap between individual samples was practically absent, as the upper conical cap, when tightened, pressed against the last (upper) sample, ensuring their tight fit to each other. The ampoule with samples was centered inside a cylindrical assembly with a diameter of 50 mm and height of 150 mm. Ammonite grade 6ZhV was used as the explosive (EX). All assembly components (detonator, EX charge, and ampoule) were installed coaxially with each other (Fig. 1).

2.2. Analytic methods

The phase composition of the products obtained after shock-wave synthesis was studied by X-ray phase analysis on a DRON-3M diffractometer. Diffraction patterns were recorded with an angular step of 0.02° and an exposure time of 1 s. Quantitative analysis of the synthesis products was determined by the corundum number method. This method involves quantitative determination of the phase composition of a multicomponent powder mixture by comparing the intensities of diffraction peaks of the studied phases with a standard – corundum (α-Al_2O_3), without the need to construct calibration curves using reference mixtures.

3. Results and Discussion

For thermodynamic calculations in the THERMO program, data for tetrafluoroethylene (C_2F_4), were used, since polytetrafluoroethylene (PTFE) is a polymer based on this monomer. The standard enthalpy of formation of C_2F_4 $\Delta H = -658.5\ kJ \cdot moL^{-1}$ was taken from the reference [20]. In studies [19, 21], optimal compositions for the W–PTFE–Al system from microdispersed powders were established based on calculations (Table 1). Table 1 presents the results of thermodynamic calculations performed using the THERMO program [22], including values of adiabatic combustion temperature (T_{ad}), as well as the proportion and phase composition of the resulting products. Previously, in studies [19, 20], it was established that in composition No. 1 with low aluminum content, self-sustaining combustion does not initiate upon local heating, but synthesis initiates under shock-wave loading, whereas in composition No. 4 with high aluminum content, self-sustaining combustion initiates upon local heating, but synthesis does not initiate under shock-wave loading.

Table 1. Characteristics of the compositions

No	Mass content, wt. %			Theoretical density, g·cm^{-3}	T_{ad}, °C	Condensed product, wt. %	Gas product, wt. %
	W	PTFE	Al				
1	76	19	5	6.93	2777	75 (W_2C)	16 (AlF_3); 3 (WF_3)
2	72	18	10	6.4	2866	74 (W_2C)	11 (AlF_3); 7 (AlF); 5 (AlF_2)
3	64	16	20	5.55	1710	66 (W_2C)	29 (AlF)
4	56	14	30	4.91	1382	57 (W_2C)	24 (AlF)

Measurements of the ignition temperature of the W–PTFE–Al system based on nanodispersed tungsten in the thermal explosion mode showed that the reaction proceeds with high intensity in all compositions (Fig. 2). The ignition intensity is characterized by the time between the onset of ignition and reaching the maximum temperature and is about 0.1 s. Initiation of reactive mixtures was observed upon reaching the temperature range of 1000–1060 °C with subsequent increase to 1400–1700 °C. The noted ignition temperature threshold significantly exceeds the phase transition points of individual components – melting of aluminum and decomposition of PTFE, confirming the heterogeneous interaction mechanism involving solid, liquid, and gaseous reagents. Experimentally recorded peak temperature values were significantly lower than the calculated adiabatic parameters. This discrepancy is explained by the combined effect of the low sample mass, contributing to heat losses, and the significant volume of gaseous products released, absorbing part of the reaction energy.

Figure 3 shows preservation ampoules after shock-wave loading. Deformation and integrity violation of all ampoules confirm that synthesis was initiated in all compositions under shock-wave loading (Fig. 3).

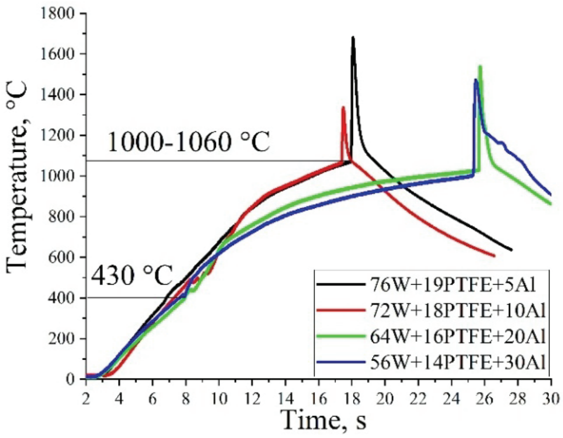


Fig. 2. Thermograms of the heating process of the studied compositions

Upon initiation of the 76W–19PTFE–5Al composition, the upper plug was ejected with partial destruction of the ampoule wall (approximately 30 % of its length), as shown in Fig. 3*a*. The 72W–18PTFE–10Al composition exhibited a more intense reaction with ejection of the upper plug and partial destruction of the ampoule wall (approximately 70 % of its length) (Fig. 3*b*). This composition demonstrated the maximum energy release among the studied systems. Upon initiation of the 64W–16PTFE–20Al composition, ampoule depressurization occurred with characteristic expansion of its upper part: the diameter increased by 12 % (Fig. 3*c*). The reaction of the 56W–14PTFE–30Al composition had the least impact on the ampoule: its hermeticity was preserved, but there was an increase in diameter in the lower part by approximately 6 % (Fig. 3*d*).

The distribution of damage regions in the ampoules allows assessing the relative sensitivity of the studied compositions to shock-wave impact. For the 76W–19PTFE–5Al and 72W–18PTFE–10Al compositions, destruction was localized exclusively in the upper part of the ampoule, while the lower section retained the original geometry without visible deformations (Fig. 3*a*, *b*). As is known [8], under cylindrical loading, maximum pressure is realized in the lower part. Initiation of compositions in the upper part of the ampoule indicates their high sensitivity to shock-wave loading, which is consistent with the results described in [19].

Deformation and destruction of ampoules with 64W–16PTFE–20Al and 56W–14PTFE–30Al compositions occurred predominantly in their lower part (Fig. 3*c*, *d*). Localization of the reaction near the ampoule bottom indicates reduced sensitivity of these compositions to shock wave impact. The use of nanodispersed tungsten powder proved to be a key factor that enabled initiation of the synthesis reaction in the 56W–14PTFE–30Al composition, whereas in [19] this composition based on microdispersed tungsten did not initiate.

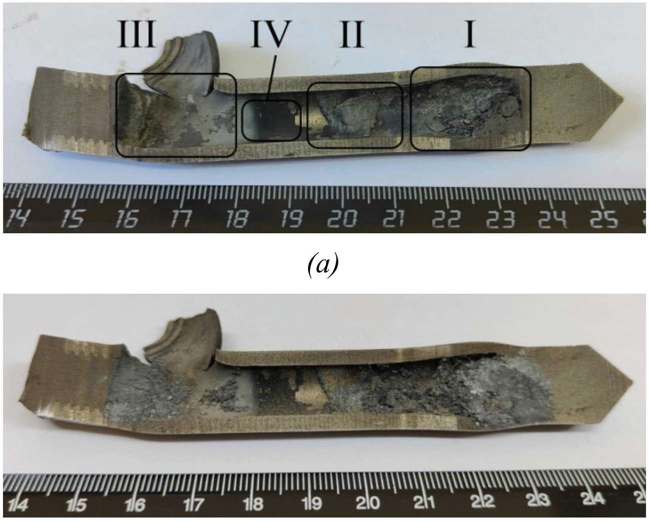
(a) (b) (c) (d)

Fig. 3. Ampoules after shock-wave loading:
a – 76W–19PTFE–5Al; *b* – 72W–18PTFE–10Al; *c* – 64W–16PTFE–20Al; *d* – 56W–14PTFE–30Al

Ampoules with 64W–16PTFE–20Al and 56W–14PTFE–30Al compositions were cut along the detonation propagation direction of the explosive. In the ampoule with the 64W–16PTFE–20Al composition, the product was preserved in the upper part, which is associated with ampoule destruction and ejection of most of the sample (Fig. 4*a*).

Reaction products were collected from four sections: beginning (I), middle (II), end (III), and directly from the ampoule walls in the middle part (IV). Their X-ray phase analysis was conducted, with results shown in Fig. 5. Products from sections I, II, and III had identical composition consisting of tungsten carbides (hexagonal WC – 35–38 wt. %, W_2C 22–26 wt. %) and tungsten aluminide (monoclinic Al_4W 32–36 wt. %). The product collected from the ampoule walls (IV) mainly consisted of aluminum fluoride (rhombohedral AlF_3 52–54 wt. %), while WC (12–15 wt. %), W_2C (12–15 wt. %), and Al_4W (13–16 wt. %) were present in approximately half the amount. Thus, gaseous aluminum fluoride (AlF_3) is released from the sample and condenses on the ampoule walls. The synthesis product formed large solid pieces, but upon exposure to air, it disintegrated into powder state (Fig. 4*b*). This effect is associated with moisture absorption from air by aluminum fluoride, forming $AlF_3·3H_2O$ in the synthesized product, which leads to its volume expansion [23, 24]. The resulting powder was pressed into tablets and dried until the tablet weight stopped decreasing, with a weight loss of 1–2 %. Dried tablets, when exposed to air for several hours, absorbed up to 1 % moisture and disintegrated similarly to the products from the preservation ampoule (Fig. 4*b*). Thus, disintegration is caused by moisture sorption from air.

During shock-wave loading of the ampoule with the 56W–14PTFE–30Al composition, synthesis occurred, which did not happen in the composition based on microdispersed tungsten [20]. The internal part of the synthesized sample had several large pores in sections I and II, as well as fine pores along the entire sample length (Fig. 6*a*).



(a)

(b)

Fig. 4. The longitudinally-sectioned ampoule with composition 64W–16PTFE–20Al after shock-wave loading: *a* – after the experiment; *b* – 170 hours later

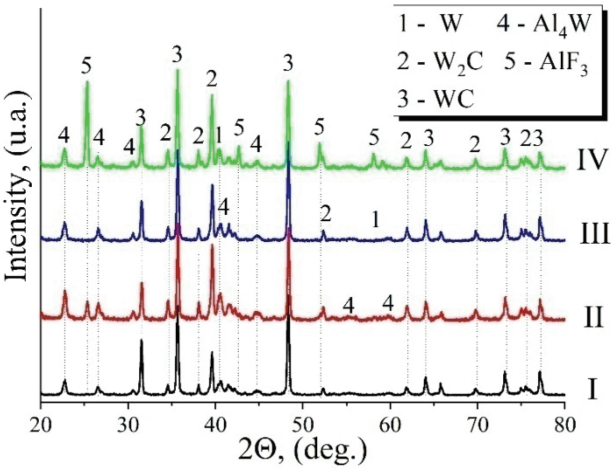
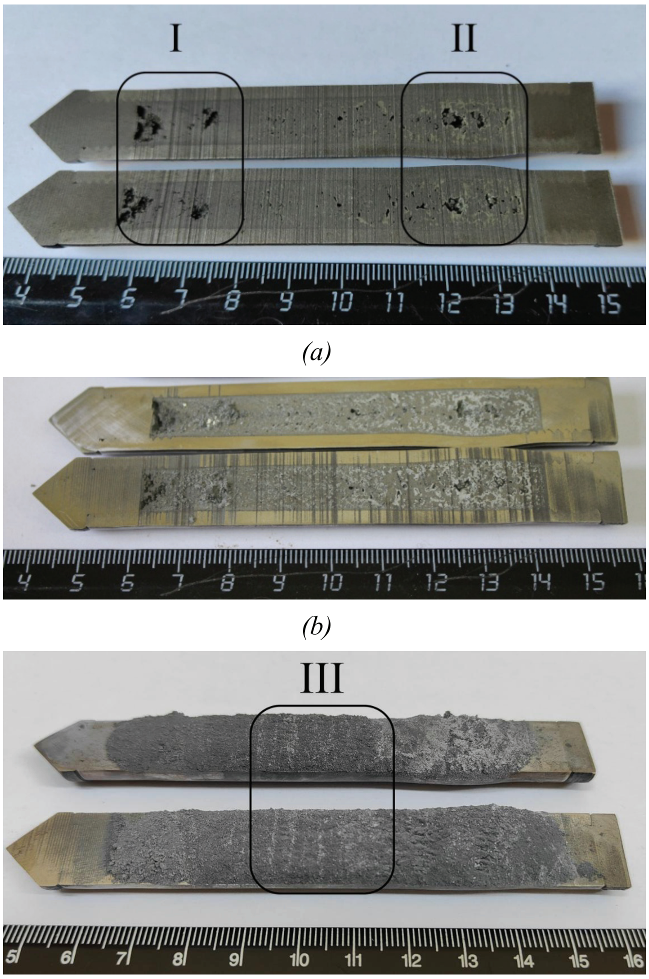


Fig. 5. XRD patterns of the synthesis products from the 64W–16PTFE–20Al ampoule after shock-wave loading



(a)

(b)

(c)

Fig. 6. The longitudinally-sectioned ampoule with composition 56W–14PTFE–30Al after shock-wave loading: *a* – after the experiment; *b* – 24 hours later; *c* – 720 hours later

The sample can be divided into three regions. The first region – 25 mm long – consists of a light-gray fine-grained phase distributed in a dark-gray phase. The second region – 20 mm long – features a characteristic 45° inclination angle of the light-gray and dark-gray phases relative to the sample axis. The third section, approximately 35 mm long, consists of a coarse-grained light-gray phase distributed in a dark-gray phase. The observed significant gradient of synthesis conditions along the sample length is due to the convergence of compression and reflection shock waves in the lower part of the preservation ampoule [19]. The shock waves also converge toward the sample center, creating uneven pressure from periphery to center, which leads to the formation of regions with different reaction intensity [1].

The resulting synthesized product represented a solid sample along the entire ampoule length (Fig. 6*a*), but after 24 hours, the beginning and end of the sample began to disintegrate (Fig. 6*b*). After more than 700 hours, the solid synthesized product disintegrated into powder state (Fig. 6*c*). To determine air moisture sorption by the synthesis products of the 56W–14PTFE–30Al composition, the powder was dried. The mass loss after drying was 2.0–2.5 %. The weight of tablets after exposure to air for 12 hours increased by 1 %, and edge crumbling of the tablet and disintegration occurred similarly to the products from the preservation ampoule.

Figure 7 shows the results of X-ray phase analysis of synthesis products from the ampoule with the 56W–14PTFE–30Al composition, taken from sections I and II, as well as after moisture absorption from section III (Fig. 6*c*). The higher intensity of

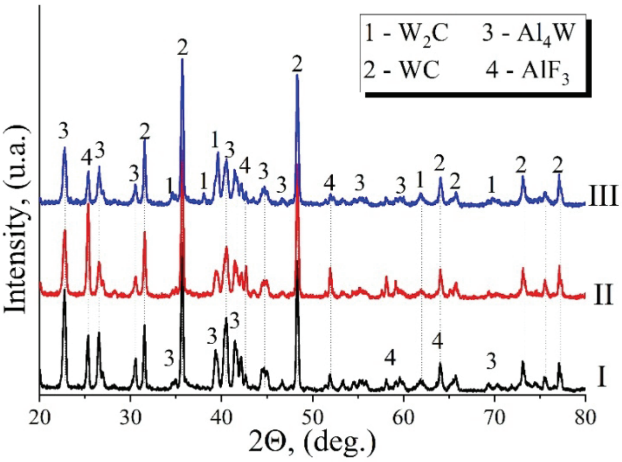


Fig. 7. XRD patterns of the synthesis products from the 56W–14PTFE–30Al ampoule after shock-wave loading

AlF_3 peaks in section 2 correlates with the observed significant deformation of the ampoule in this area, indicating more intense reactions with formation of volatile products specifically in the lower part of the sample. The intensity of AlF_3 peaks in the synthesis products after moisture absorption (section III) decreases, but the phase composition is identical to the synthesis products from sections II and III of the sample before moisture absorption.

4. Conclusion

As a result of the conducted studies, the parameters of thermal explosion in the W–PTFE–Al system using nanodispersed tungsten were determined. For all studied compositions, the reaction is characterized by high rate of occurrence. The time interval between ignition at 1000–1060 °C and reaching peak temperatures in the range of 1400–1700 °C is about 0.1 s. The use of nanodispersed tungsten enabled initiation of synthesis under shock-wave loading in all compositions. The 76W–19PTFE–5Al and 72W–18PTFE–10Al compositions are highly sensitive to shock-wave loading, as they initiate in the region with relatively low pressure. The 64W–16PTFE–20Al and 56W–14PTFE–30Al compositions demonstrate low sensitivity. The use of nanodispersed tungsten made the synthesis products hygroscopic. The main phases in all synthesis products are tungsten carbides (WC, W_2C) and tungsten aluminide (Al_4W). The hygroscopicity of the synthesis products led to their disintegration into powder state. Disintegration is associated not with phase composition change, but with the physical process of water sorption.

As a result of shock-wave loading of the 56W–14PTFE–30Al composition in a cylindrical preservation ampoule, formation of three morphologically distinct regions was revealed. The observed heterogeneity indicates the existence of a significant gradient of synthesis conditions (temperature, pressure, and reaction duration) along the sample length. The 72W–18PTFE–10Al composition demonstrated the most intense energy release under shock-wave loading, as evidenced by the greatest ampoule destruction (70 % of length).

5. Funding

This research was supported by Russian Science Foundation No. 24-29-00787, https://rscf.ru/project/24-29-00787/

Финансирование

Исследование выполнено за счет средств гранта Российского научного фонда 24-29-00787, https://rscf.ru/project/24-29-00787/

6. Conflict of interests

The authors declare no conflict of interest.

Конфликт интересов

Авторы заявляют об отсутствии конфликта интересов.

References

1. Zhou Q, Hu Q, Wang B, Zhou B, et al. Fabrication and characterization of the Ni–Al energetic structural material with high energy density and mechanical properties. *Journal of Alloys and Compounds*. 2020;832:154894. DOI: 10.1016/j.jallcom.2020.154894

2. Pisarev SP, Rogozin VD, Bogdanov AI, Arisova VN, et al. Effect of thermal treatment on phase composition explosive pressing of tungsten boride and nickel powders. *Izvestiya Volgogradskogo gosudarstvennogo tehnicheskogo universiteta*. 2019;2:34-38. (In Russ.)

3. Ananev SY, Deribas AA, Drozdov AA, Dolgoborodov AY, et al. Dynamic compaction of Ni and Al micron powder blends in cylindrical recovery scheme. *Journal of Physics: Conference Series*. 2015;653:012037. DOI:10.1088/1742-6596/653/1/012037

4. Hastings DL, Dreizin EL. Reactive structural materials: preparation and characterization. *Advanced Engineering Materials*. 2018;20(3):1700631. DOI: 10.1002/adem.201700631

5. Adamenko NA, Kazurov AV, Agafonova GV, Savin DV. Structure formation in nickel-polytetrafluorethylene composite materials upon explosive pressing of powders. *Materialovedenie = Inorganic Materials: Applied Research*. 2020;11(4):982-990. DOI: 10.1134/S2075113320040036 (In Russ.)

6. Ignatieva LN, Zverev GA, Adamenko NA, Kazurov AV, et al. Features of forming the metal-fluoropolymer composites by method of explosive pressing. *Journal of Fluorine Chemistry*. 2019;217:58-62. DOI:10.1016/j.jfluchem.2018.11.008

7. Adamenko NA, Kazurov AV, Savin DV, Agafonova GV. Structure and thermophysical properties of polytetrafluoroethylene-aluminum composite materials produced by explosive pressing. *IOP Conference Series: Materials Science and Engineering*. 2018;450:032044. DOI:10.1088/1757-899X/450/3/032044

8. Thadhani NN. Shock compression processing of powders. *Advanced Materials and Manufacturing Processes*. 1988;3(4):493-549. DOI:10.1080/10426918808953217

9. Batsanov SS. Features of solid-phase transformations induced by shock compression. *Uspehi himii = Russian Chemical Reviews*. 2006;75(7):601-616. DOI:10.1070/RC2006v075n07ABEH003613 (In Russ.)

10. Guo J, Zhang QM, Zhang LS, Guo XG, et al. Reaction behavior of polytetrafluoroethylene/al granular

composites subjected to planar shock wave. *Propellants, Explosives, Pyrotechnics*. 2017;42(3):300-307. DOI: 10.1002/prep.201600115

11. Zelepugin SA, Ivanova OV, Yunoshev AS, Zelepugin AS. Destruction of cylindrical ampoules containing solid phase reaction mixtures under explosive loading. *Letters on Materials*. 2015;5(4):468-472. DOI: 10.22226/2410-3535-2015-4-468-472

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

13. Alymov MI, Pervukhin LB, Rogachev AS, Pervukhina OL, et al. Combination of SHS and shock wave compacting for production of composite materials. *Letters on Materials*. 2014;4(3):153-158. DOI:10.22226/2410-3535-2014-3-153-158

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. 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

16. Yu ZS, Fang X, Gao ZR, Wang HX, et al. Mechanical and reaction properties of Al/TiH_2/PTFE under quasi-static compression. *Advanced Engineering Materials*. 2018;20(7):1800019. DOI:10.1002/adem.201800019

17. 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

18. Shekhawat D, Vauth M, Pezoldt J. Size dependent properties of reactive materials. *Inorganics*. 2022;10(4):56. DOI:10.3390/inorganics10040056

19. 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

20. Chase MW. NIST–JANAF thermochemical tables. *Journal of Physical and Chemical Reference Data*. 1998;1951.

21. Seropyan SA, Saikov IV, Malakhov AYu, Saikova GR. Shock wave loading of reactive materials of the W–PTFE–Al powder system in cylindrical ampoules. *Izvestia Volgograd State Technical University*. 2022;(11):87-93. DOI:10.35211/1990-5297-2022-11-270-87-93 (In Russ.)

22. Shiryaev AA. Thermodynamics of SHS: Modern approach. *International Journal of Self-Propagating High-Temperature Synthesis*. 1995;4:351-362.

23. Roodenko K, Halls MD, Gogte Y, Seitz O, et al. Nature of hydrophilic aluminum fluoride and oxyaluminum fluoride surfaces resulting from XeF_2 treatment of Al and Al_2O_3. *The Journal of Physical Chemistry C*. 2011;115(43):21351-21357. DOI:10.1021/jp207839w

24. Zhang Z, Zhang L, Zhu L, Fu M, et al. Effect of hydrated aluminium fluoride on phase transformation and morphology evolution of alumina. *Journal of the Australian Ceramic Society*. 2025;61(1):321-331. DOI: 10.1007/s41779-024-01135-2

Information about the authors / Информация об авторах

Ivan V. Saikov, Cand. Sc. (Eng.), Leading Researcher, Deputy Director, Merzhanov Institute of Structural Macrokinetics and Materials Science, RAS (ISMAN), Chernogolovka, Russian Federation; ORCID 0000-0003-1473-2854; e-mail: revan.84@mail.ru

Stepan A. Seropyan, Junior Research, ISMAN, Chernogolovka, Russian Federation; ORCID 0000-0002-3714-3983; e-mail: stepan.seropyan@yandex.ru

Denis V. Shakhray, Cand. Sc. (Phys. and Math.), Head of the Department of Extreme States of Matter, Federal Research Center of Problems of Chemical Physics and Medicinal Chemistry, RAS, Chernogolovka, Russian Federation; ORCID 0009-0006-1192-1157; e-mail: shakhray@icp.ac.ru

Сайков Иван Владимирович, кандидат технических наук, ведущий научный сотрудник, заместитель директора, Институт структурной макрокинетики и проблем материаловедения им. А. Г. Мержанова РАН (ИСМАН), Черноголовка, Российская Федерация; ORCID 0000-0003-1473-2854; e-mail: revan.84@mail.ru

Серопян Степан Арутюнович, младший научный сотрудник, ИСМАН, Черноголовка, Российская Федерация; ORCID 0000-0002-3714-3983; e-mail: stepan.seropyan@yandex.ru

Шахрай Денис Владимирович, кандидат физико-математических наук, заведующий отделом экстремальных состояний вещества, Федеральный исследовательский центр проблем химической физики и медицинской химии РАН, Черноголовка, Российская Федерация;ORCID 0009-0006-1192-1157; e-mail: shakhray@icp.ac.ru

Alexandr V. Smirnov, Junior Research, ISMAN, Chernogolovka, Russian Federation; ORCID 0009-0003-3350-4440; e-mail: smirnov_av@ism.ac.ru

Gulnaz R. Saikova, Cand. Sc. (Eng.), Senior Researcher, ISMAN, Chernogolovka, Russian Federation; ORCID 0000-0002-6542-7123; e-mail: gulnaz-84@mail.ru

Смирнов Александр Викторович, младший научный сотрудник, ИСМАН, Черноголовка, Российская Федерация; ORCID 0009-0003-3350-4440; e-mail: smirnov_av@ism.ac.ru

Сайкова Гульназ Рафиковна, кандидат технических наук, старший научный сотрудник, ИСМАН, Черноголовка, Российская Федерация; ORCID 0000-0002-6542-7123; e-mail: gulnaz-84@mail.ru

Received 07 October 2025; Revised 17 November 2025; Accepted 18 November 2025