SPECIFIC FEATURES OF COMBUSTION OF NANOTHERMITES BASED ON NANOALUMINUM AT LASER INITIATION

V. G. Kirilenko[1], L. I. Grishin[2,3], A. Yu. Dolgoborodov[1,2,3], M. A. Brazhnikov[1], M. L. Kuskov[1], and G. E. Valyano[2]

[1]N. N. Semenov Federal Research Center for Chemical Physics of the Russian Academy of Sciences, 4 Kosygin Str., Moscow 119991, Russian Federation
[2]Joint Institute for High Temperatures of the Russian Academy of Sciences, 13-2 Izhorskaya Str., Moscow 125412, Russian Federation
[3]National Research Nuclear University MEPhI, 31 Kashirskoe Sh., Moscow 115409, Russian Federation

Abstract: The work deals with thermites based on mixtures of nanosized Al with oxides of copper, bismuth, molybdenum, and nickel. New data have been obtained on the minimum initiation energy and burning rate depending on the density and the ratio of the components. The thermites were initiated by a laser diode pulse with a wavelength of 808 nm and a radiation power density of up to 800 W/cm^2. The parameters of ignition and burning were recorded using a multichannel pyrometer and high-speed video camera. The brightness temperature of nanothermite combustion products has been measured. The effect that inert light-absorbing nanosized additives have on the threshold parameters of laser-induced initiation and on the burning rate of the mixtures has been studied. Based on the results obtained, the assumptions were made regarding the mechanism of initiation and the reaction process induced by laser pulse radiation.

Keywords: nanothermites; laser ignition; burning rate; ignition delay; light-absorbing additives; porosity

DOI: 10.30826/CE22150110

Figure Captions

Figure 1 The SEM images of nAl (*a*), nBi_2O_3 (*b*), $nMoO_3$ (*c*) and nanothermite (NT): Al/CuO 19/81 (*d*), Al/Bi_2O_3 15/85 (*e*), and Al/MoO_3 30/70 (*f*)

Figure 2 Surface structure of Al/CuO ($\Psi = 1.1$) samples of different porosity: (*a*) $\varepsilon = 90\%$; and (*b*) $\varepsilon = 78\%$

Figure 3 Schematic of the experimental setup: *1* — control computer; *2* — power supply and control unit; *3* — laser diode; *4* — focusing lenses; *5* — camcorder Phantom Miro LC-310; *6* — protective glass plates; *7* — target with sample; *8* — optical fiber; *9* — pyrometer; and *10* — digital oscilloscope

Figure 4 Oscillograms: *1* — laser pulse ($t_{\mathrm{imp}} = 1820$ μs); and *2* — TTL pulse ($t_{\mathrm{imp}} = 1900$ μs)

Figure 5 Characteristic records of radiation at NT ignition: signals from the rear (*1*) and front (*2*) surfaces

Figure 6 Critical energy density of NT Al/CuO ($\Psi = 1.1$) ignition on porosity: *1* — 207 W/cm^2; and *2* — 650 W/cm^2

Figure 7 Burning velocity vs. porosity for NT Al/CuO ($\Psi = 1.1$): *1* — data of the present authors; *2* — data [12]; and *3* — data [18]

Figure 8 Effect of carbon black content on time delay and critical energy of NT Al/CuO ($\Psi = 1.1$, $\varepsilon = 89\%$) initiation

Figure 9 Brightness temperature of combustion products: *1* — Al/CuO ($\Psi = 1.1$); *2* — Al/CuO ($\Psi = 1.1$) +1% carbon black; *3* — Al/MoO_3 ($\Psi = 1.2$); and *4* — Al/Bi_2O_3 ($\Psi = 1.6$)

Figure 10 Initial stage of NT laser ignition

Figure 11 Reaction development after laser pulse completion: signals from the front (*1*) and rear (*2*) surfaces

Figure 12 Frames of high-speed shooting of reaction propagation over the sample surface at laser initiation of NT at $\varepsilon = 89\%$

Figure 13 Frames of high-speed shooting of reaction propagation over the sample surface of NT at $\varepsilon = 52\%$

Figure 14 Burning velocity vs. tube length for NT Al/CuO ($\Psi = 1.1$, $\varepsilon = 87\%$)

Figure 15 Frames of high-speed shooting of reaction propagation of NT Al/CuO ($\Psi = 1.1$, $\varepsilon = 87\%$) in a glass tube of 45-millimeter length

Figure 16 Change in the burning velocity of NT Al/CuO ($\Psi = 1.1$, $\varepsilon = 87\%$) along the axis of the tube of 45-millimeter length

Table Captions

Table 1 Ignition temperature of NT by the hot surface

Table 2 Parameters of laser initiation of porous NT

References

1. Brish, A. A., I. A. Galeev, B. N. Zaitsev, E. A. Sbitnev, and L. V. Tatarintsev. 1966. Laser-excited detonation of condensed explosives. *Combust. Explo. Shock Waves* 2(3):81–82.
2. Sivan, J., Y. Haas, D. Grinstein, Sh. Kochav, G. Yegudayev, and L. Kalontarov. 2015. Boron particle size effect on B/KNO_3 ignition by a diode laser. *Combust. Flame* 162(2):516–527.
3. Herreros, D. N., and X. Fang. 2017. Laser ignition of elastomer-modified cast double-base (EMCDB) propellant using a diode laser. *Opt. Laser Technol.* 89:21–26.
4. Kim, Ji Hoon, Myung Hoon Cho, Kyung Ju Kim, and Soo Hyung Kim. 2017. Laser ignition and controlled explosion of nanoenergetic materials: The role of multi-walled carbon nanotubes. *Carbon* 118:268–277. doi: 10.1016/j.carbon.2017.03.050.
5. Korotkikh, A. G., I. V. Sorokin, E. A. Selikhova, and V. A. Arkhipov. 2020. Effect of B, Fe, Ti, Cu nanopowders on the laser ignition of Al-based high-energy materials. *Combust. Flame* 222:103–110.
6. Hu, Peng, Mingchun Xian, Lizhi Wu, Haonan Zhang, Yinghua Ye, and Ruiqi Shen. 2021. Laser ignition of a laser-thermal differential composite system based on non-uniform absorption. *Chem. Eng. J.* 421(2). doi: 10.1016/j.cej.2020.127869.
7. Uhlenhake, K. E., D. Olsen, M. Gomez, M. Örnek, M. Zhou, and S. F. Son. 2021. Photoflash and laser ignition of full density nano-aluminum PVDF films. *Combust. Flame* 233. doi: 10.1016/j.combustflame.2021.111570.
8. Zarko, V. E., and A. A. Gromov, eds. 2016. *Energetic nanomaterials: Synthesis, characterization, and application*. Amsterdam: Elsevier. 485 p.
9. Pantoya, M., and J. Granier. 2006. The effect of slow heating rates on the reaction mechanisms of nano and micron composite thermite reactions. *J. Therm. Anal. Calorim.* 85:37–43.
10. Bhattacharya, S., A. K. Agarwal, T. Rajagopalan, and V. K. Patel, eds. 2019. *Nano-energetic materials: Energy, environment and sustainability*. Springer, Singapore. 305 p.
11. Pantoya, M., and J. Granier. 2004. Laser ignition of nanocomposite thermites. *Combust. Flame* 138(4):373–383.
12. Sanders, V., B. Asay, T. Foley, B. Tappan, A. Pacheco, and S. Son. 2007. Reaction propagation of four nanoscale energetic composites (Al/MoO_3, Al/WO_3, Al/CuO, and Bi_2O_3). *J. Propul. Power* 23:707–714.
13. Egorshev, V. Y., V. P. Sinditskii, and K. K. Yartsev. 2013. Combustion of high-density CuO/Al nanothermites at elevated pressures. *10th Autumn Seminar (International) on Propellants, Explosives and Pyrotechnics Proceedings*. 287–290.
14. Petre, C., D. Chamberland, T. Ringuette, S. Ringuette, S. Paradis, and R. Stowe. 2014. Low-power laser ignition of aluminum/metal oxide nanothermites. *Int. J. Energetic Materials Chemical Propulsion* 13:479–494.
15. Aduev, B. P., M. V. Anan'eva, A. A. Zvekov, *et al.* 2014. Micro-hotspot model for the laser initiation of explosive decomposition of energetic materials with melting taken into account. *Combust. Explo. Shock Waves* 50(6):704–710.
16. Kolesov, V. I., and D. I. Patrikeyev. 2017. Gorenie nanotermitov v vakuume [Combustion of nanothermites at subatmospheric pressure]. *Goren. Vzryv (Mosk.) — Combustion and Explosion* 10(1):69–72.
17. Saceleanu, F., M. Idir, N. Chaumeix, and J. Z. Wen. 2018. Combustion characteristics of physically mixed 40 nm aluminum/copper oxide nanothermites using laser ignition. *Front. Chem.* 6:465. doi: 10.3389/fchem.2018.00465.
18. Gordeyev, V. V., M. V. Kazutin, N. V. Kozyrev, A. O. Kashkarov, I. A. Rubtsov, K. A. Ten, and S. I. Rafeychik. 2018. Issledovanie mekhanizma goreniya nanotermitnykh sistem [Investigation of the mechanism of combustion nanothermite systems]. *Polzunovskiy Vestnik* 2:96–101.
19. Kirilenko, V. G., L. I. Grishin, A. Yu. Dolgoborodov, and M. A. Brazhnikov. 2020. Lazernoe initsiirovanie nanotermitov Al/CuO i Al/Bi_2O_3 [Laser initiation of nanothermites Al/CuO and Al/Bi_2O_3]. *Goren. Vzryv (Mosk.) — Combustion and Explosion* 13(1):145–155.
20. Dolgoborodov, A. Yu., V. G. Kirilenko, M. A. Brazhnikov, L. I. Grishin, M. L. Kuskov, and G. E. Valyano. 2021. Ignition of nanothermites by a laser diode pulse. *Defence Technology* 18(2):194–204. doi: 10.1016/j.dt.2021.01.006.
21. Guen, M. Y., and A. V. Miller. 1961. Method for production of metal aerosols. SU Patent 814432.
22. Kuskov, M. L., A. N. Zhigach, I. O. Leipunskii, A. N. Gorbachev, E. S. Afanasenkova, and O. A. Safronova. 2019. Combined equipment for synthesis of ultrafine metals and metal compounds powders via flow-levitation and crucible methods. *IOP Conf. Ser. — Mat. Sci.* 558:012022.
23. Dolgoborodov, A. Yu., V. G. Kirilenko, A. N. Streletskii, I. V. Kolbanev, A. A. Shevchenko, B. D. Yankovskii, S. Y. Ananev, and G. E. Valyano. 2018. Mekhanoaktivirovanyy termitnyy sostav Al/CuO [Mechanoactivated thermite composition Al/CuO]. *Goren. Vzryv (Mosk.) — Combustion and Explosion* 11(3):117–124.
24. Streletskii, A. N., I. V. Kolbanev, G. A. Vorobieva, A. Y. Dolgoborodov, V. G. Kirilenko, and B. D. Yankovskii.

2018. Kinetics of mechanical activation of Al/CuO thermite. *J. Mater. Sci.* 53(19):13550–13559.

25. Yankovsky, B. D., A. Yu. Dolgoborodov, L. I. Grishin, and S. Yu. Ananev. 2021. Study of combustion wave propagation in linear charges from mechanically activated thermite mixtures. *J. Phys. Conf. Ser.* 1787:012017. doi: 10.1088/1742-6596/1787/1/012017.
26. Gogulya, M. F. 1988. *Temperatury udarnogo szhatiya kondensirovannykh sred* [Temperature of shock compression of condensed matter]. Moscow: MEPhI. 68 p.
27. Grishinin, S. G., A. A. Solodovnikov, and G. P. Startsev. 1958. Fotograficheskiy metod izmereniya temperatury istochnikov sveta [Photographic method for measuring the temperature of light sources]. *Trudy Komissii po pirometrii pri VNIIM* [Proceedings of the Commission on Pyrometry at VNIIM]. Moscow: Standartgiz. Vol. 1.

Received December 24, 2021

Contributors

Kirilenko Vladimir G. (b. 1956) — Candidate of Science in physics and mathematics, senior research scientist, N. N. Semenov Federal Research Center for Chemical Physics of the Russian Academy of Sciences, 4 Kosygin Str., Moscow 119991, Russian Federation; vladkiril@gmail.com

Grishin Leonid I. (b. 1993) — junior research scientist, Joint Institute for High Temperatures of the Russian Academy of Sciences, 13-2 Izhorskaya Str., Moscow 125412, Russian Federation; Ph.D. student, National Research Nuclear University MEPhI, 31 Kashirskoe Sh., Moscow 115409, Russian Federation; lenya-grishin@mail.ru

Dolgoborodov Alexander Yu. (b. 1956) — Doctor of Science in physics and mathematics, chief research scientist, N. N. Semenov Federal Research Center for Chemical Physics of the Russian Academy of Sciences, 4 Kosygin Str., Moscow 119991, Russian Federation; head of laboratory, Joint Institute for High Temperatures of the Russian Academy of Sciences, 13-2 Izhorskaya Str., Moscow 125412, Russian Federation; teacher, National Research Nuclear University MEPhI, 31 Kashirskoe Sh., Moscow 115409, Russian Federation; aldol@ihed.ras.ru

Brazhnikov Michael A. (b. 1966) — Candidate of Science in pedagogy, senior research scientist, N. N. Semenov Federal Research Center for Chemical Physics of the Russian Academy of Sciences, 4 Kosygin Str., Moscow 119991, Russian Federation; birze@inbox.ru

Kuskov Michael L. (b. 1972) — Candidate of Science in physics and mathematics, senior research scientist, N. N. Semenov Federal Research Center for Chemical Physics of the Russian Academy of Sciences, 4 Kosygin Str., Moscow 119991, Russian Federation; mkuskov72@gmail.com

Valyano Georgii E. (b. 1945) — senior research scientist, Joint Institute for High Temperatures of the Russian Academy of Sciences, 13-2 Izhorskaya Str., Moscow 125412, Russian Federation; gev06@bk.ru