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ZH. K. YELEMESOVA^{1,*}, Z. A. MANSUROV^{1,2}, B. T. LESBAYEV^{1,2}, R. SHEN³

¹Al-Farabi Kazakh National University, Almaty, Republic of Kazakhstan,

²Institute of Combustion Problems, Almaty, Republic of Kazakhstan,

³Nanjing University of Science and Technology, Nanjing, China

LASER IGNITION OF ENERGETIC MATERIALS BASED ON CARBON CONTAINING METAL OXIDE PROPELLANT

Abstract. An experimental study to investigate the laser ignition using a diode laser for carbon containing energetic compositions based on metal oxide propellant in order to develop more reliable and greener laser ignitors for direct initiation of the propellant was conducted. Samples of the propellant were ignited using a 974 nm near-infrared diode laser. Laser beam parameters including laser energy, beam width and pulse width were investigated to determine their effects on the ignition performance in terms of delay time, rise time and burn time of the propellant which was arranged in several different configurations. The results have shown that the smaller beam widths, longer pulse widths and shorter laser energy resulted in shorter ignition delay times and overall burn times, however, which increasing the amount of laser energy transferred to the material resulted in no significant reduction in either delay time or overall burn time. The tested propellant well responded to laser ignition, an expansion that supports continued research into the development of laser-based propellant ignitors.

Key words: laser ignition, ignition delay, combustion, energy materials, activated carbon, metal oxide.

Introduction. In recent years efforts have been made to eliminate primary explosives from ignition mechanisms, primarily because of the associated safety and environmental hazards. Historically, several accidents have resulted from the use of high explosive materials, which can become unpredictable if they are not carefully stored and monitored. For example, high temperatures experienced during storage are known in affecting the energetic materials service life and, in extreme cases, lead to potentially fatal occasions. Governments around the world have introduced measures to discourage the use of heavy metals in ignitors and other explosive devices with the introduction of new legislation, such as REACH. This has meant that the search for alternative solutions has become not only desirable, but necessary. Direct ignition of energetic materials using laser technology could eliminate the problems associated with traditional ignitors, by removing the primary explosives and heavy metals [1-3].

Laser ignition offers several advantages over electrical ignition mechanisms, including immunity to electromagnetic interference, no metal component insertion, the reliability and reproducibility inherent of laser systems and the ease with which the optical fibers could be utilized to install multipoint initiation. It has become an important and interesting topic not only to researchers, but for manufacturers of explosive ignitors, due to the modern advancements in the development of lasers which are more compact, more cost effective, and more efficient in

comparison to those lasers used during the first laser ignition attempts in the 1960's [4-7]. Despite the extensive research which has been carried out into the laser ignition of energetic materials including propellants [13-15], few laser-based ignitors have been developed for real world use to date and the details of these systems are not currently available in the open literature.

Many energetic materials that are typically used in low energy electro-explosive devices (EED's) can be ignited when heated by a laser of sufficient power density. In the past decade, high-power solid-state laser diode technology has matured to the point that it is a viable candidate for replacement of EED's in applications where reliability and safety are concerns [8]. Historically, the development of optical initiators has been based on off-the-shelf laser diodes and solid state lasers. In order to reverse this trend and optimize the laser source specifically for ignition of energetic materials, the fundamental process of ignition must be better understood. In this work we analyze the thermal-radiative transport in energetic materials that are being heated by a laser beam, and investigate the effects of material properties and laser beam shape on the minimum energy threshold for ignition.

Since the laser was first introduced as an ignition source for energetic materials numerous studies involving laser ignition of both deflagration and detonation have been carried out and published. However, none or only a few studies have been devoted to diode laser ignition of unconfined secondary explosives by means of an optical fiber. There are at least two possible reasons for this apparently weak interest. The first possibility is that studies of the ignition of confined explosives are more useful when constructing laser ignition systems. The second possibility originates from the earlier shown strong pressure dependence in the threshold ignition energy. The energy needed to ignite a secondary explosive at atmospheric pressure is therefore high [9-11].

Ignition by a laser beam is an external ignition method which offers a number of advantages when compared to other ignition methods. A non-exhaustive list includes: high temporal and spatial precision and accuracy, minimal ignition delay, no need for premixing, simultaneous ignition of multiple combustion chambers via optical fiber coupling, an increased ignition probability for a wide range of mixture ratios and initial chamber conditions (from vacuum to high pressure), as well as an electromagnetic interference (EMI) which is well below permissible levels for space flight. Studies comparing laser and electric spark ignition for fuel rich mixtures has shown that laser ignition ensures a higher ignition probability for lower pressures and this is independent of the initial chamber pressure [12]. Laser ignition can be performed in a number of different ways, by direct means, where by the laser energy is absorbed by the propellants directly upon impingement of the laser beam, or indirectly, whereby the laser energy is transmitted from the laser beam to the propellants via another medium, such as metal particles.

Due to the potential to increase both the safety and performance of initiation systems, the use of laser radiation to initiate energetic materials remains a topic of

interest. Once the fundamental details of the interactions of laser energy and energetic materials are understood, the laser source and delivery hardware can be designed specifically for this purpose.

EXPERIMENTAL

Materials and Samples. Activated carbon was obtained in the Laboratory of Functional Nanomaterials of the Institute of Combustion Problems (Almaty, Kazakhstan). Mechanical treatment (15 min) of ammonium nitrate (purity 99%) powder was carried out in a planetary mill. Ammonium nitrate was used as an oxidizer in the condensed mixture with a diameter of 212–250 μm . Magnesium (Mg) was used as a fuel, and its diameter was 200 μm . The diameter of the metal oxide particles was 30–40 μm , and it acted as a catalyst. Nitrate cellulose was used as a binder. The diameter and length of the compositions were 3 and 10 mm, respectively.

Measurement of Laser Ignition Characteristics. The schematic diagram illustrated in figure 1 shows the set up used for laser ignition of a sample. A fibre-coupled laser diode operating at a wavelength of 974 nm was used as the igniting source, a laser diode controller was used to set pulse width of 300 ms and laser power (up to 40 W with ~ 6 mW resolution), and an external pulse generator (RS Components 610–629) was used for triggering the laser. The laser beam output was focused with a focusing lens (50 mm diameter and 50 mm focal length) onto the surface of a sample material. The beam diameter incident on the lens was ~ 50 mm. The spot sizes on sample surfaces varied from 0.7 to 3.5 mm in diameters (± 0.05 mm error). A glass block was used for a strand propellant to sit on for ignition. For laser initiation, 30 samples were prepared and burned in with each composite.

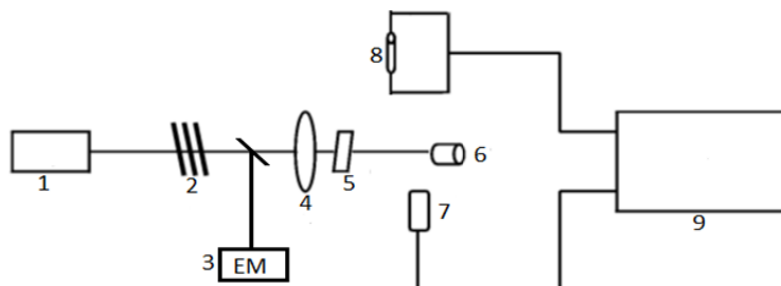
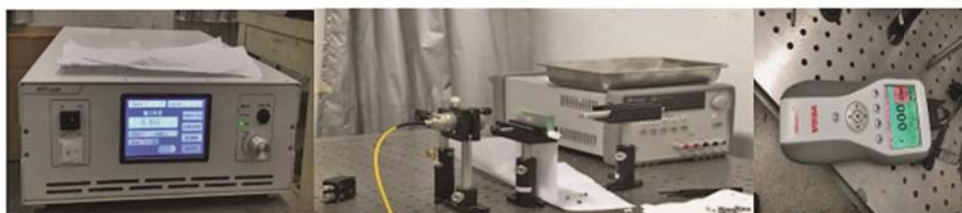


Figure 1 – Experimental set up for laser ignition: 1 – laser diode; 2 – attenuator split; 3 – energy meter; 4 – focusing lens; 5 – glass plate; 6 – sample; 7 – optic detector; 8 – sampling resistance; 9 – data analysis system

Upon correct set up of the equipment, a sample holder containing the propellant material was placed on a height adjustable stage below the focusing lens and the sample surface was positioned at the laser focus. Following exposure to the laser beam, the sample material would be heated up and ignited with sufficient laser power. The ignition characteristics of the propellant were studied by examining changes in delay time, rise time and burn time across a range of beam widths, laser powers and pulse durations.

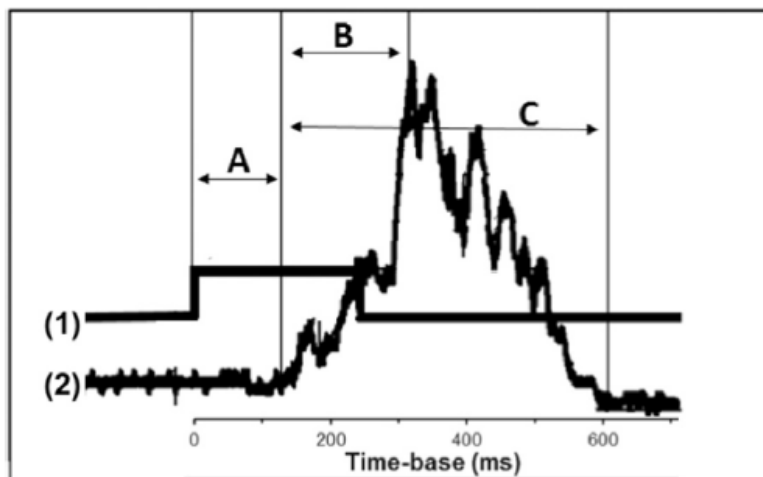


Figure 2 – Oscilloscope traces of (1) laser pulse and (2) the ignited flame with measures: (A) delay time, (B) rise time and (C) burn time

Figure 2 shows graphically the delay time, rise time and burn time measurement definitions. Delay time (A) is taken to be the time between the start of the laser pulse and onset of deflagration of propellant, rise time (B) is taken to be the time between deflagration onset and ignition and burn time (C) is taken to be the time between onset and end of deflagration.

RESULTS AND DISCUSSION

Finding the ignition energy threshold of the propellant was important as this benchmarked the minimum energy requirements for subsequent testing. In each case, a «Go/No-Go» result was recorded for whether or not the ignition took place. Table shows the results of the spent laser energy and ignition delay to initiate for each composition.

According to the results, we can see that the energy spent on laser initiation of the composition decreases (figure 3). As seen for the initiation of the basic composition (AN/Mg) which does not contain activated carbon with metal oxide was spent 25.97 J of energy. And for the initiation of the composition AN/Mg/C-CuO used 4.35 J of energy, almost four times less energy was spent.

The results of the spent laser energy and ignition delay to initiate for each composition

№	Compositions	Ignition energy, J	Ignition delay, ms
1	AN/Mg	25.97	902
2	AN/Mg/Carbon	9.31	810
3	AN/Mg/C-NiO	6.88	688
4	AN/Mg/C-CuO	4.35	506

*AN – ammonium nitrate.

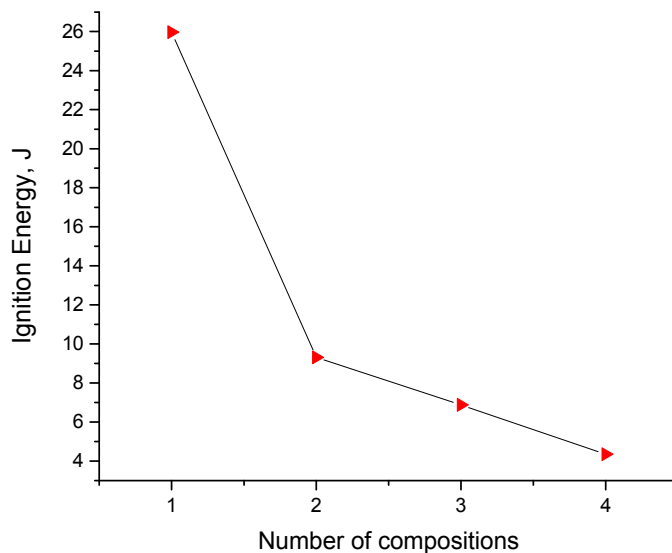


Figure 3 – Ignition energy Dependencies on the compositions

The thermal properties of the energetic material play an important part in addition to the laser energy. This is due to the fact that the activated carbon itself in the form of as a fuel contains a large amount of energy. Metal oxides (CuO/NiO) can be the catalyst for our AN-based propellant system. Ignition by a low-medium laser energy of continuous wave is a complicated process, which includes transfer and dissipation of the heat generated by laser and also the energetic material decomposition in a long-time scale.

The delay time is of particular interest as it can affect both system safety and system response times. Figure 4 presents the dependencies of the ignition delay time on the compositions. As shown, to initiate the compositions with a decrease in energy expended, the delay of the ignition time was also reduced. Ignition delay of basic AN/Mg composition was 902 ms and for the AN/Mg/C/CuO composition reduced to 506 ms. It could be said that the composition with activated carbon based on metal oxides reacts quickly to inflammation and is sensitive to initiation.

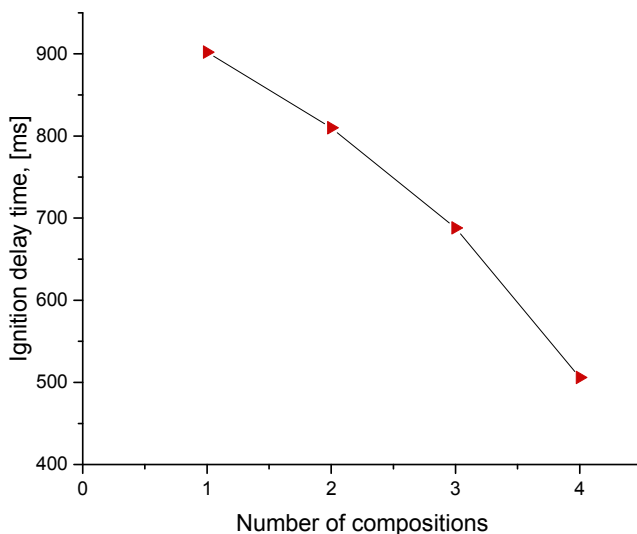


Figure 4 – Dependencies of the ignition delay time on the compositions

Conclusion. This study shows that laser ignition limit for the propellant depends on laser energy and ignition delay and demonstrates that AN/Mg/C/MeO propellant is a good candidate for laser ignition for several reasons. Firstly, the propellant does not require the addition of any optical sensitizers in order to achieve reliable and sustainable ignition, meaning that chemical properties are retained. Secondly, the propellant burned sustainably at a laser energy of ≥ 4.35 J, providing that ignition delay was 506 ms. The findings of this study support the development of a laser-diode propellant ignitor based on direct ignition of the propellant charge without the need for sensitive pyrotechnics or primary explosives.

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Резюме

Ж. К. Елемесова, З. А. Мансуров, Б. Т. Лесбаев, Р. Шен

МЕТАЛ ОКСИД НЕГІЗІНДЕГІ КӨМІРТЕКҚҰРАМДЫ ЭНЕРГЕТИКАЛЫҚ КОМПОЗИЦИЯЛЫҚ ПРОПЕЛЛАНТТЫҢ ЛАЗЕРЛІК ТҰТАНУЫ

Тікелей тұтануды тиімді ету мақсатында метал оксиді негізіндегі құрамында көміртек бар энергетикалық композициялық пропеллантқа диод лазерін қолдану арқылы тәжірибелік зерттеу жүргізілді. Отын үлгілеріне 974 нм-лік жақын инфрақызыл диодтың лазері пайдаланылды. Лазерлік сәуле параметрлері, соның ішінде лазерлік энергия, сәулесінің ені және серпін ені, әртүрлі конфигурацияда орналасқан кідірту уақытын көтеру мен отынның жағу уақытында тұтану сипаттамаларына әсерін анықтау үшін зерттелді. Алынған нәтижелер бойынша сәуленің кішірек ені, импульстің үлкен ені және қысқа лазерлік энергиясы қысқа тұтанудың кешігу уақытына және толық жану уақытына әкелетінін көрсетті, алайда лазерлік энергияның көбеюі тұтанудың уақытын азайтпайды. Зерттелінген отын лазерлік тұтануға оң әсер етті және ол лазерлік отын тұтатқыштарын игеруде жүргізіліп жатқан зерттеулерді қолдайды.

Түйін сөздер: лазерлік тұтану, тұтану кешігуі, жану, энергетикалық материалдар, белсендірілген көмір, металл оксиді.

Резюме

Ж. К. Елемесова, З. А. Мансуров, Б. Т. Лесбаев, Р. Шен

ЛАЗЕРНОЕ ИНИЦИИРОВАНИЕ
УГЛЕРОДСОДЕРЖАЩИХ ЭНЕРГЕТИЧЕСКИХ КОМПОЗИЦИЙ
НА ОСНОВЕ МЕТАЛОКСИДНОГО ПРОПЕЛЛАНТА

Экспериментальное исследование было проведено для изучения лазерного воспламенения с использованием диодного лазера для углеродсодержащих энергетических композиций на основе металлоксидного пропелланта с целью разработки более надежных и более зеленых лазерных воспламенителей для прямого инициирования пропелланта. Образцы топлива зажигались с использованием 974 нм ближнего инфракрасного диодного лазера. Параметры лазерного луча, включая энергию лазера, ширину луча и ширину импульса, были исследованы для определения их влияния на характеристики зажигания с точки зрения времени задержки, времени нарастания и времени горения топлива, которое было расположено в нескольких различных конфигурациях. Результаты показали, что меньшая ширина луча, большая ширина импульса и более короткая энергия лазера приводят к более коротким временам задержки зажигания и полному времени горения, однако увеличение количества лазерной энергии, передаваемой материалу, не приводит к значительному сокращению времени задержки или общее время записи. Испытанный пропеллانت хорошо реагировал на лазерное воспламенение, расширение, которое поддерживает продолжающиеся исследования в разработке лазерных воспламенителей топлива.

Ключевые слова: лазерное инициирование, задержка зажигания, горение, энергетические материалы, активированный уголь, оксид металла.

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