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Laser ignition of elastomer-modified cast double-base (EMCDB) propellant using a diode laser

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ABSTRACT

An experimental study was conducted to investigate laser ignition using a diode laser for elastomer-modified cast double-base (EMCDB) propellant in order to develop more liable and greener laser ignitors for direct initiation of the propellant. Samples of the propellant were ignited using a 974 nm near-infrared diode laser. Laser beam parameters including laser power, 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 higher laser powers resulted in shorter ignition delay times and overall burn times, however, there came a point at 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 propellant tested responded well to laser ignition, a discovery which supports continued research into the development of laser-based propellant ignitors.

1. 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. High temperatures experienced during storage, for example, are known to affect the service life of energetic materials and, in extreme cases, lead to potentially fatal cook-off events. 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.

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 fibres can be utilised 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 [1]. Despite the extensive research which has been carried out into the laser ignition of energetic materials [2–15] 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.

EMCDB propellant is a smokeless propellant used in the space industry, which is known for being able to overcome problems of brittleness which can occur in CDB propellants at low temperatures. There has been no published research regarding the laser ignition of EMCDB propellant, although some research has been carried out relating to other propellant materials, e.g. CDB and extruded DB propellants [15]. It has been shown that CDB propellant has high optical absorption (~95%) across the electromagnetic (EM) spectrum and responds well to laser ignition in its manufactured state.

This paper presents results and analysis of systematic tests on laser ignition of EMCDB propellant and the effects of laser parameters. A diode laser of continuous wave (CW) was selected as the igniting source due to its miniature size, low cost and ease of system integration for future applications in the space industry. The results from this study would help determine whether EMCDB propellant would respond well to any laser-based ignition mechanism developed in the future and build on the limited knowledge of laser ignition of propellants by testing the ignition characteristics of a propellant which has not yet been studied.

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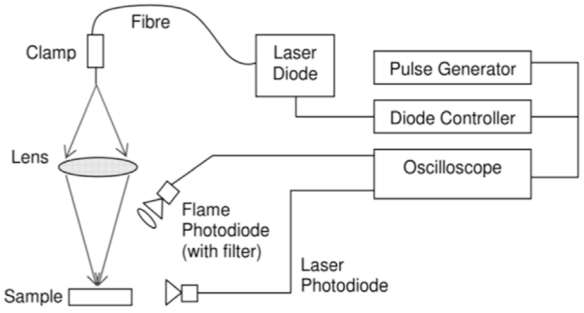

Fig. 1. Experimental set up for laser ignition.

2. Experimental

2.1. Materials

Two types of EMCDB propellant were investigated during this study: cylindrical-shaped granular propellant with a length of 1 mm and a diameter of 1 mm, and strand propellant of 3 mm×3 mm×35 mm. The propellant material was used as received (Roxel UK) and its compositions typically contain nitrocellulose (20%), nitroglycerin (60%), plasticisers (4.5%), additives (4.5%) and an elastomer (3%) [16].

2.2. Set up

The schematic diagram illustrated in Fig. 1 shows the set up used for laser ignition of a sample. A fibre-coupled laser diode (IPG PLD60-A-974) operating at a wavelength of 974 nm was used as the igniting source, a laser diode controller (ThorLabs ITC4020) was used to set pulse width (from 10 µs to CW with 10 µs resolution) 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 (i.e. f/# of illumination ~1). The spot sizes on sample surfaces varied from 0.7 to 3.5 mm in diameters (± 0.05 mm error). The sample holder for granular propellant was an aluminium plate that has holes of 4 mm diameter and 4 mm depth for filling or a linear groove for linear arrangement of the grains. A glass block was used as the sample holder for a strand propellant to sit on for ignition. Two photodiodes (Centronic BPX65) were used to detect the light from the laser pulse and the propellant burn respectively; both were connected to a digital oscilloscope (Agilent Technologies DSO5054A) which was used to record and measure temporal history of the ignition event. An optical filter that filters out laser was placed on a photodiode to only collect the combustion signature.

2.3. Measurements

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 flame information was then captured by the photodiode and subsequently recorded on the oscilloscope, ready for analysis. 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. Fig. 2 shows graphically the delay time, rise time and burn time measurement definitions which were used throughout the experiments. 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. Following each ignition test under various ignition parameters, the oscilloscope traces of the signals were recorded and the ignition delay, rise time and burn time were measured and analysed. For this study, the laser beam size used during experiments was between 0.7 mm and 3.5 mm, the power was up to 40 W and the pulse width was varied between 20 ms and 1000 ms.

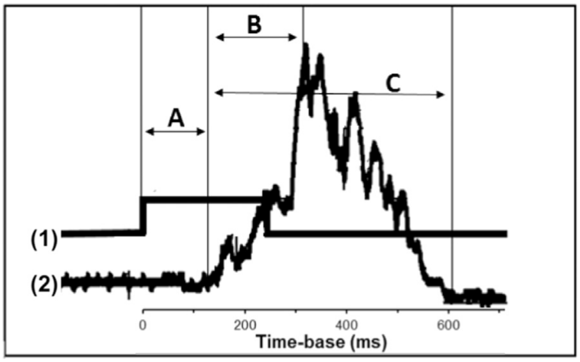

Fig. 2. Oscilloscope traces of (1) laser pulse and (2) the ignited flame with measures: (A) Delay Time, (B) Rise Time and (C) Burn Time.

3. Results and discussion

The laser ignition was tested for propellants of both granular and strand types under various laser parameters including laser power, beam size and pulse width. The ignition results were obtained and analysed in following sections for the two types, respectively.

3.1. Granular propellant

3.1.1. Effects of laser power and beam sizes

Finding the ignition power threshold of the propellant was important as this benchmarked the minimum power requirements for subsequent testing. Laser ignition was tested using a laser spot size of 0.7 mm, a pulse width of 300 ms, and various laser powers. In each case, a 'Go/No-Go' result was recorded for whether or not the ignition took place. Upon successful ignition, a number of laser powers over a very small range were tested in order to determine a consistent threshold. This involved, of ten repetitions, 100% ignition. From these experiments the ignition threshold was found to be 0.8 W. Subsequently, the lower limit of laser power during testing was set at 1 W.

Ignition tests were carried out using various laser powers and laser spot sizes and the results were analysed in terms of ignition map (delay time versus laser power), rise time and burn time. Fig. 3 shows the ignition map for a laser spot size of 0.7 mm and laser power of up to 35 W. Each data point (delay time) was an average over 7 repeated tests at a laser power and the error bars of ~10% were the average of the relative standard deviations (the ratio of standard deviation to the delay time at a data point) of the eleven data points. This plot with a trendline (dotted line) indicates how quickly the ignition took place at various laser powers, and shows that as the power increases, the ignition delay decreases sharply at lower powers and tends to a saturation level at medium laser powers, from a delay time of 330 ms at a power of 1 W to almost instantaneous ignition at 25 W and above. The measurement errors in delay time may be mainly attributed to the inhomogeneity in the sample surface as the grain sizes were comparable to the size of the laser spot incident on samples.

Based on the heat transfer theory in laser ignition [17], the effect of igniting laser power on ignition delay may be estimated in Eq. (1) when the radial heat dissipation prior to ignition is not taken into account.