Optics and Laser Technology Volume 89, March 2016, pp. 21-26
DOI:10.1016/j.optlastec.2016.09.033

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 974nm 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.

Keywords: Laser ignition, Ignition delay, EMCDB Propellant

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.

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 x 3 mm x 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 mm 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.

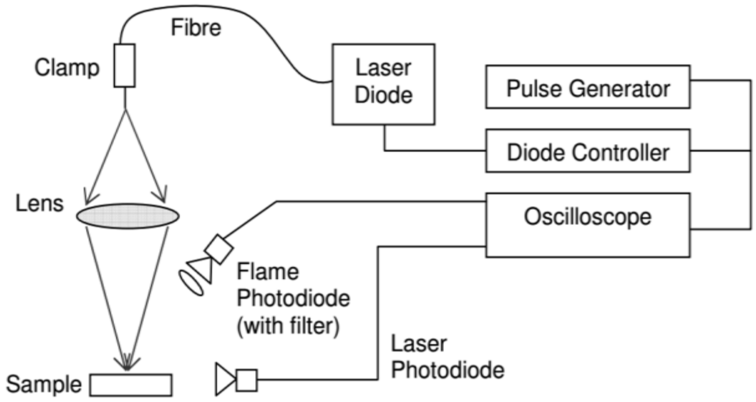

Fig. 1 Experimental set up for laser ignition

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.

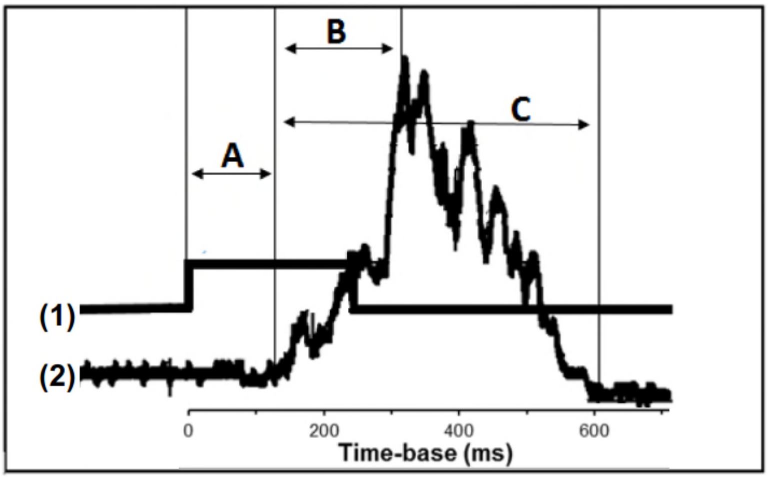

Fig. 2 Oscilloscope traces of (1) laser pulse and (2) the ignited flame with measures: (A) Delay Time, (B) Rise Time and (C) Burn Time

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.

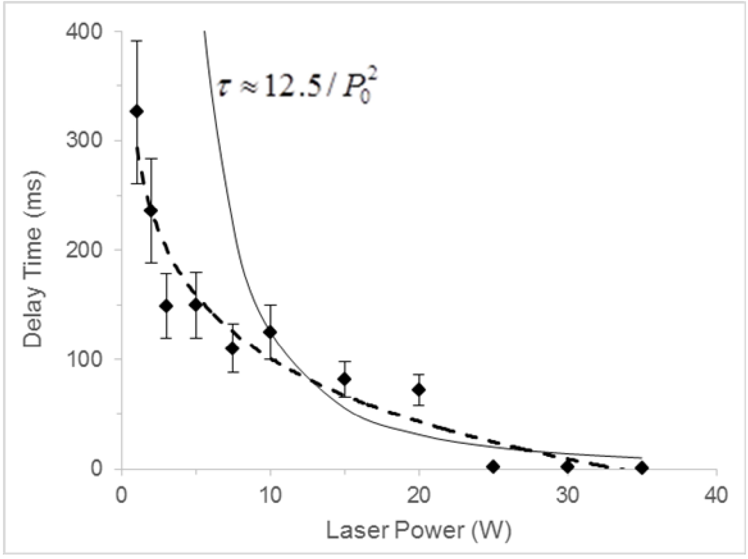

Fig. 3 Ignition map for 0.7mm beam width

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

$$\left(\alpha\tau/\pi\right)^{1/2} \approx k\Delta T/(2I_0) \tag{1}$$

Where, τ is the ignition delay, α thermal diffusivity, k thermal conductivity of the material, ΔT temperature increase to the ignition and I_o laser power density. For the material, ignition temperature is 168 ^{o}C and thermal diffusivity, α and thermal conductivity, k are currently unknown. With a laser beam of 0.7 mm at room temperature environment (e.g. 20 ^{o}C), ignition delay is expressed as

$$\sqrt{\tau} \approx 5\times10^{-5}\frac{k}{\sqrt{\alpha}}\cdot\frac{1}{P_0} \tag{2}$$

where P_0 is laser power. The thermal properties of the energetic material play an important part in addition to the laser power. By inputting the measured delay time at a medium laser power (e.g. 125 ms at 10 W) to equation (2), an empirical value is estimated to draw a fitting curve in Fig. 3 as $\tau \approx 12.5/P_0^2$. It is shown that the curve doesn't well fit at low-medium laser powers, which may be due to the radial heat dissipation that is not taken into account in Equation (1). Ignition by a low-medium laser power of continuous wave (CW) 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. Therefore, the ignition map (ignition delay versus laser power) represents a practical trend of these thermal effects and empirically determines the igniting laser power for an ignition delay time.

The subsequent laser beam spot sizes tested showed a similar trend, as seen in Fig. 4 where, for different laser beam spot sizes, the delay time varies greatly at low powers and tends to a saturation level at high powers. Seven shots were averaged for each data point in Fig. 4. For small laser spots of 0.7 mm and 1.4 mm, their difference in delay time was big across all laser powers, which was expectedly attributed to the much higher (4 times) power density over 0.7 mm spot than 1.4mm spot, in spite that smaller spots may cause more radial heat dissipation [18]. The largest laser spot size, 3.3 mm appeared to produce the quickest ignition among all spot sizes except for 0.7 mm although its power density was lower. The results for 3.3 mm were not entirely representative, considering that the percentage error for this set of results was, on average, 31% and that a high percentage error or large variability was evident across all the results. The results do show, however, the importance of laser spot size when considering delay time and that ignition delay is dependent of both power density and spot size. The delay time is of particular interest as it can affect both system safety and system response times.

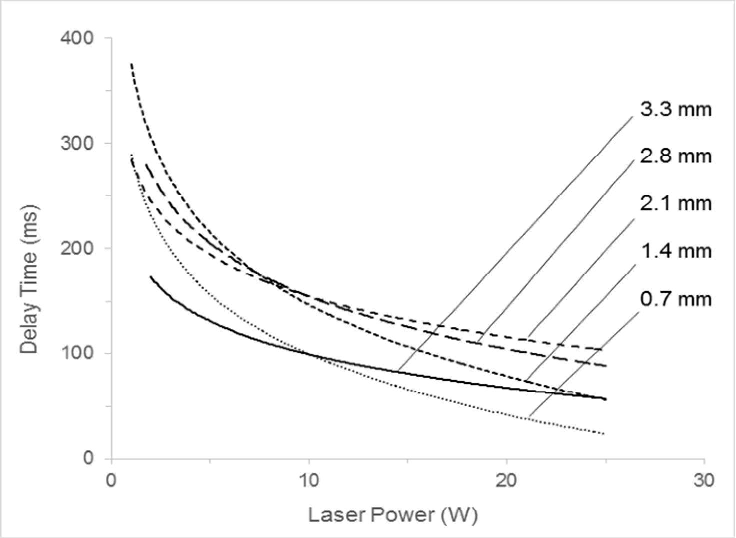

Fig. 4 Ignition map for various beam widths

Fig. 5 shows the ignition rise times at a set of laser powers across various laser spot sizes (0.7 mm, 1.4 mm, 2.1 mm, 2.8 mm and 3.3 mm). The rise time for larger beam widths (in Fig. 5a) can be seen to decrease as laser power increases, rapidly at lower laser powers, and then minimally at higher laser powers, which has a similar trend to ignition delay. This is due to the fact that at higher laser powers, more energy is passed to the sample material more quickly and therefore the temperature is raised further above the ignition threshold required, resulting in a faster initial burn. These results also show that the larger beam width resulted in a longer rise time as a result of lower power density. For the smaller laser spot sizes (in Fig. 5b), there was no obvious relationship between either spot size and rise time or laser power and rise time, with both graphs containing several peaks and troughs, appearing to be random. This may due to the comparable sizes (0.7 mm and 1.4 mm) of the laser spots to those of propellant grains (~ 1mm diameter and ~ 1mm length) and thus poor reproducibility of the volume and density of ignited sample in the ignitions.

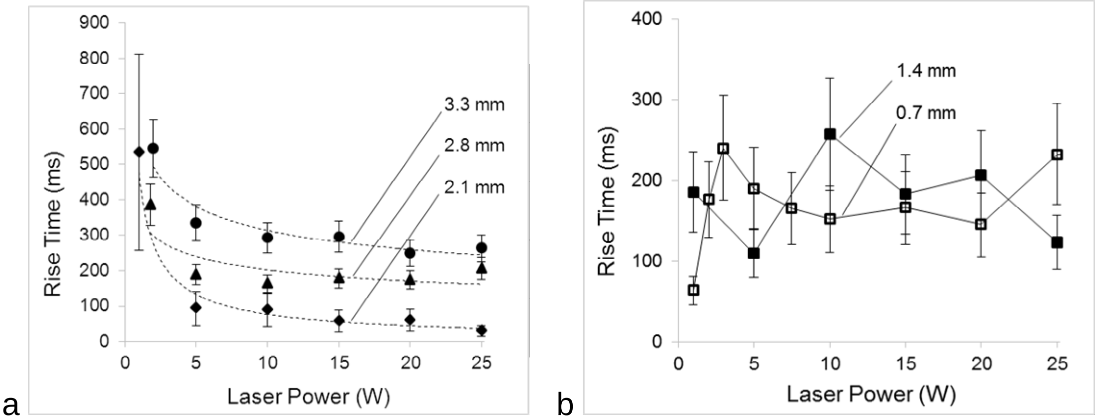

Fig. 5 Ignition rise time versus laser power at various beam widths: a) 2.1 mm, 2.8 mm and 3.3 mm; b) 0.7 mm and 1.4 mm.

The average percentage error for rise time across all results was 30%, which is fairly high. During experiments it was noted that there were two types of burn induced in the propellant material; a slow, sparky burn and a rapid, “firey” burn. The rapid burn tended to result in a faster rise time which meant that, considering most of the samples reacted with the more progressive burn, variances in the results were introduced. It is thought that the nature of the propellant material means that the way in which it reacts is not always consistent. When it is manufactured, propellant is coated with carbon black, an optical sensitizer. Due to the fact that the spread of carbon black is not consistent throughout a whole batch of propellant, the material can sometimes react differently to the same set of circumstances. It is important to draw attention to the fact that the results for rise time with large error percentages due to the fast burn were not considered anomalous as the fast burning reaction happened regularly enough for the authors to accept that this particular event was characteristic of the sample material.

The effect of laser spot size on burn time was more pronounced at larger spots. At the sizes of 3.3mm, 2.8mm and 2.1mm the burn time was seen to decrease as laser power was increased (Fig. 6a). This is because that a larger amount of energy is transferred to the material, therefore converting more energy to thermal energy, raising the temperature above the threshold and leading more quickly to a sustained burn. The burn time reached a constant of ~0.45 s when laser power was high (> 10 W) which may be mostly dependent of the burn rate of the material. As with the results for rise time, the effect of laser power and spot size on burn time was not consistent for the sizes of 0.7 mm and 1.4 mm, both diameters displaying rather flat lines in the laser power vs burn time graph

(Fig. 6b). The average percentage error seen for burn time was markedly better than that of rise and delay time at just 13%.

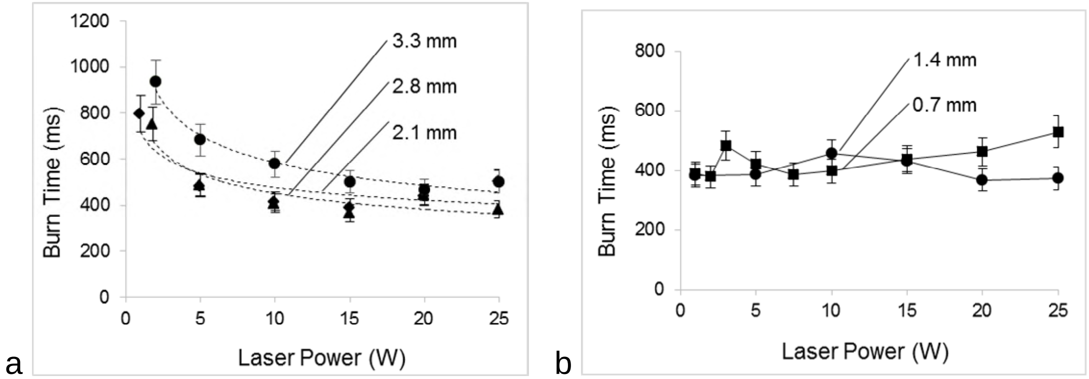

Fig. 6 The effect of laser power on burn time for various laser spot sizes: a) 2.1 mm, 2.8 mm and 3.3 mm; b) 1.4 mm and 0.7 mm.

3.1.2 Effect of pulse width

A set of laser pulse widths were applied to the ignition tests to study the effect on laser threshold power at a given laser spot size of 0.7 mm. The minimum laser powers to ignite versus pulse width were obtained and plotted in Fig. 7 with a log-log plot (on the right side) with the fit by $P_0 \approx 20/\sqrt{\tau}$ (normalized to 100 ms pulse width). Each data point was an average of 5 repeated tests. The average error was 3% (i.e. an average of relative standard deviations at all data points), with a maximum variance from the average result of 10% across all experiments. It shows that as pulse width was increased the ignition power threshold of the material decreased, rapidly at short pulse and much slowly at long pulse. When pulse width was increased beyond a time of 100 ms the effect on ignition threshold power became less noticeable, with a difference in pulse width of 100 ms and 1000 ms resulting in less than 2 W variance in the threshold power, in comparison to the decrease of ~28 W due to the increase of pulse width from 20 ms to 100 ms. This result is not unexpected considering that for ignition, a minimum thermal energy is required to be transferred to the propellant and heat it up beyond its ignition temperature. In longer pulse duration the dissipation or loss of laser induced heat increases and the required laser energy to ignite increases, restricting the further decrease in laser power threshold. The effect of pulse width is highly significant and worth considering when using lasers as an ignition mechanism. The results indicated that the ignition threshold depends on both laser power and the pulse width, the power threshold was as low as around 0.8 W for an intermediate pulse width (e.g. 300 ms).

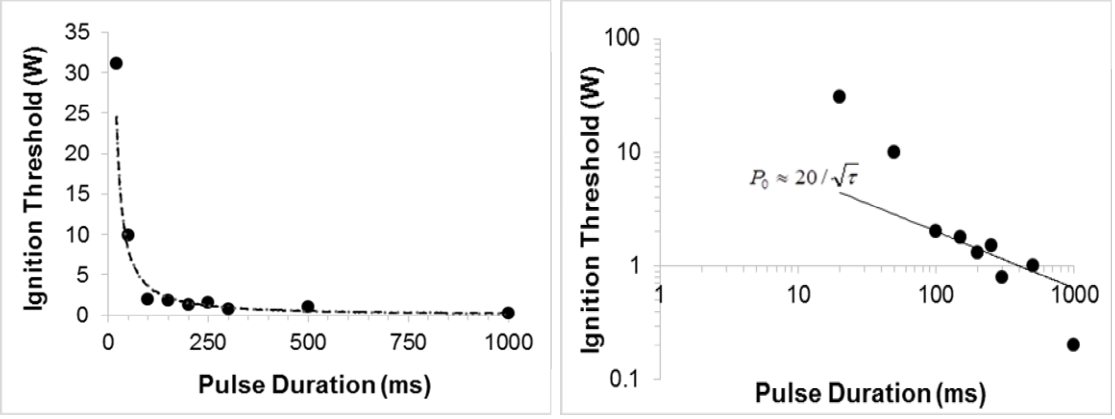

Fig. 7 The effect of pulse duration on ignition threshold at a laser spot size of 0.7 mm

3.1.3 Effect of grain arrangement

In order to observe the effect of propellant arrangement on overall burn time, ten grains were arranged linearly in a sample tray and ignited from one end by a 0.7mm laser beam, with a pulse width of 300 ms. The overall burn time was recorded in each of ten repeated tests. The average burn times for various laser powers are shown in Fig. 8. These results suggest that the laser power had no evident effect on the overall burn time of propellant arranged in this configuration, with a burn time of around 4 s for laser powers of up to 25 W. The reason for this is that the laser beam is only focused onto a single grain, as opposed to several grains in previous experiments; hence the ignition energy must be transferred linearly from grain to grain. This means that once the sustainable ignition threshold of 0.8 W is exceeded the burn progression is unaffected by laser power.

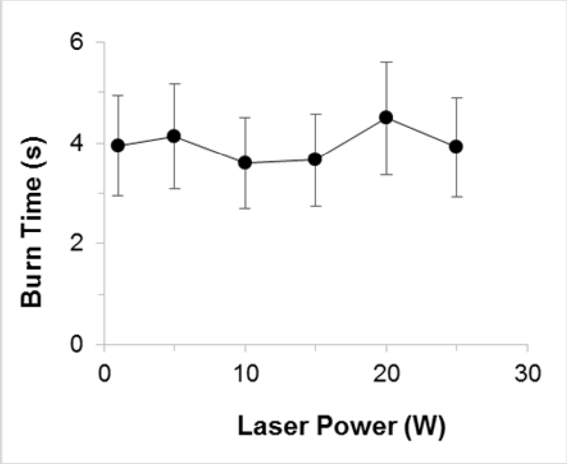

Fig. 8 The effect of laser power on overall burn time for linearly arranged propellant grains.

In comparison to the propellant arranged in the holes of the aluminium sample tray, the burn time was increased by a factor of ~10, from approximately 0.4 s to 4 s. This demonstrates that there is a much longer burn time when igniting granular propellant arranged in a linear configuration. It is shown that the burn rate of the propellant is mostly determined by the way of transferring igniting thermal energy internally.

There was an average error of ~25% for the burn time of linearly arranged grains. It is believed to derive from the burning nature of the propellant material, where the burning itself was usually sparky and slow, but occasionally developed into a faster burn with no sparking. The reason why this would sometimes happen is not known, but may be thought to derive from a combination of factors including the place at which the laser beam hits the propellant material, slight variations in the EMCDB propellant composition and differences in the arrangement of the propellant on the sample tray.

3.2 Strand Propellant

3.2.1 Effect of ignition point

EMCDB propellant in strand form was used in laser ignition experiment to develop an understanding of the effect that altering the point of ignition would have on the burn time and burn rate. For the study, propellant strands (3 mm x 3 mm x 35 mm) were ignited at end-point and mid-point respectively, with laser beam of 0.7 mm and pulse width of 300 ms at a set of powers of up to 25 W. The average burn time over 10 repeated ignition tests at each laser power was shown in Fig. 9, where the percentage error was 10% on average for mid-point ignition and 34% for end-on ignition.

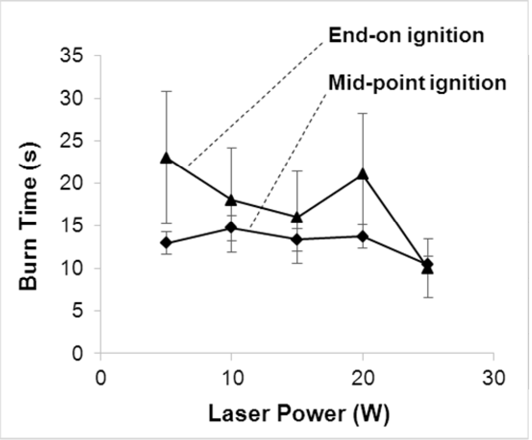

Fig. 9 The effect of laser power on burn time for strand propellant

It was found that the burn time of the strand propellant was approximately 23 s for end-on ignition, reducing to approximately 13 s for mid-point ignition at a laser power of 5 W, which could be due to the burn progression from the mid-point to the two ends of the strand. Therefore, for mid-point ignition the burn rate was significantly faster at lower laser powers, ~2.7 mm/s at 5W in comparison to ~1.5 mm/s for end-point ignition; however, the difference was less noticeable at 25 W, where the burn rates for both of ignition points were the same (3.3 ~ 3.5 mm/s) within the measurement error. These results also show that the average burn rate increased from 1.5 mm/s to 3.3 mm/s between 5 W and 25 W for end-on ignition, demonstrating that the laser power used to ignite the material does have a direct effect on the rate of burning. It may be attributed the fact that higher laser power induced higher heat flux in the ignition. The relationship between the laser power and the burn time was more noticeable with end-on ignition. For mid-point ignition, there was a less drastic drop from a burn time of 13 s (burn rate of 2.7 mm/s) at 5 W to 10 s (burn rate of 3.3 mm/s) at 25 W, despite the fact that the general trend in data was the same.

4. CONCLUSIONS

This study shows that laser ignition threshold for the propellant depends on both laser power and pulse length for a given spot size and demonstrates that EMCDB 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. The propellant burned sustainably at a laser power of ≥0.8 W in all tested configurations, providing that pulse width was in excess of 300 ms. Laser pulse width had a drastic effect on ignition threshold, with the ignition threshold increasing to 32 W at a pulse width of 20 ms, in comparison to the 0.8 W ignition threshold at 300 ms pulse width.

It was found that burning characteristics could be closely controlled by altering laser parameters. By using higher laser powers and smaller beam widths, the delay time and burn time of the propellant can be reduced significantly. To illustrate, at a beam width of 0.7 mm the delay time can be reduced from 325 ms to ~ 2 ms by increasing laser power from 1 W to 25 W. Larger beam widths (> 2.1 mm) were found to have the effect of increasing burn time and rise time. The burn time was increased by a factor of ten by arranging propellant grains in a linear fashion. For strand propellant, the burn time can be reduced by igniting at the centre of its length, which indicates a feasibility to speed up propellant burning by igniting position and multi-point ignition.

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. A further research will be necessarily carried out to investigate the ignition reliability of EMCDB propellant, especially regarding the distribution and degree of compaction of the propellant grains and its combustion performance in a confined condition.

ACKNOWLEDGEMENT

The authors would like to thank Dr Philip Gill and Roxel Ltd. UK for providing the propellant materials for this study.

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