

# Laser Ignition of Al-MoO<sub>3</sub> Thermites

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## 1 Introduction

Over the past two decades, advancements in high-power and fiber optic lasers—driven by rapid progress in telecommunications and laser-based manufacturing—have led to the development of compact, durable, and highly efficient laser systems. The ability to transmit laser power through fiber optic cables allows for localized initiation of energetic materials, enabling ignition in environments that were previously unattainable. While laser-based ignition has been extensively studied for other uses, such as propellants, there is also significant interest in applying this process to thermites.

Thermites are highly reactive compositions consisting of a metal and a metal oxide, where the metal—having a stronger affinity for oxygen—reduces the oxide to its elemental form while releasing a large amount of heat. A well-known example is the aluminum–iron oxide reaction, which produces aluminum oxide and elemental iron. Thermites can release up to 5 MJ/kg of heat, with most reaction products remaining in the condensed phase. By adjusting the particle size and morphology of the reactants, the sensitivity and combustion rate can be tailored for specific applications. The emergence of nanometric-scale powders has further expanded the possibilities for thermite formulations, as discussed in recent reviews by Comet et al. [1], Kabra et al. [2], Polis et al. [3], and Fahd et al. [4].

Research into laser ignition of thermites, particularly nanothermites, has gained traction in recent years. Petre et al. [5] investigated ignition thresholds and delay times for Al–CuO, Al–MoO<sub>3</sub>, and Al–Bi<sub>2</sub>O<sub>3</sub> using diode lasers at 661, 532, and 445 nm, aiming to determine the energy required for initiation. Monk et al. [6] explored CO<sub>2</sub> laser ignition (10.6 μm) of aluminum- and zirconium-based thermites, formulated with various oxidizers (WO<sub>3</sub>, MoO<sub>3</sub>, CuO, Fe<sub>2</sub>O<sub>3</sub>, and Bi<sub>2</sub>O<sub>3</sub>) using reactive milling techniques. Fahd et al. [7] examined Al/KClO<sub>4</sub> compositions with nitrocellulose binders, identifying ignition thresholds under 532 nm laser irradiation. While these studies have demonstrated the feasibility of laser ignition for nanothermites, a comprehensive analysis of their critical power–energy ignition envelope across a broad range of particle sizes has not been investigated.

This study focuses on the widely investigated aluminum–molybdenum trioxide (Al–MoO<sub>3</sub>) thermite system, aiming to establish correlations between its combustion characteristics—such as minimum propagation diameter and propagation speed variation with sample diameter—and its laser ignition parameters. A fiber laser operating at 1070 nm will be used, and both micrometric and nanometric thermite formulations will be examined.

## 2 Methodology

### 2.1 Experimental Setup

Figure 1 presents the experimental setup. The laser used in this study is an IPG Photonics YLR-300/3000-QCW-MM-AC Ytterbium fiber laser, operating at a wavelength of 1070 nm. It can function in both pulsed mode, delivering up to 3 kW of power, and continuous mode, providing 300 W. To measure laser energy, a UP55N-300F-H12 Gentec-EO power meter is employed, capable of handling up to 300 W of average power and an average power density of 45 kW/cm<sup>2</sup>.

High-speed videography serves as the primary method for analyzing thermite propagation velocity. A Photron FASTCAM SA5 high-speed camera, paired with a SIGMA 70-300 mm F4-5.6 DG MACRO zoom lens, captures the reaction at 1000 frames per second. This frame rate ensures a balance between image resolution for accurate speed measurements and a sufficiently wide field of view to record the entire sample.

To focus the laser beam after it exits the collimator, a 400-mm plano-convex lens is employed. Additionally, a laser debris shield with an anti-reflective coating is placed in front of the optics to safeguard both the collimator and lenses from thermite particles ejected during the experiment.

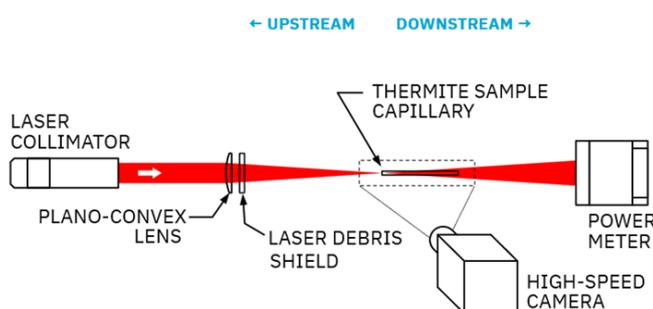
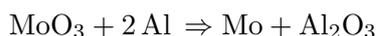


Figure 1: Experimental testing facility. The field of view of the camera is denoted in dotted lines.

### 2.2 Thermite Mixture Preparation

Experiments are performed on aluminum–molybdenum trioxide systems in both micrometric and nanometric scales. The micrometric scale composition, composed of spherical aluminum powder and molybdenum (VI) oxide, is mixed at a stoichiometric 2:1 fuel-to-oxidizer ratio. The nanometric scale mixture is prepared at a 2.4:1 molar ratio. The nanometric aluminum manufacturer specifies an active aluminum content of 90%, and thus a corrected mass of aluminum is calculated accordingly.



To maximize safety, a “wet” mixing technique was selected for preparing both mixtures. The two components are combined in approximately 15 mL of isopropyl alcohol, creating a suspension that is then ultrasonicated<sup>1</sup> in two 15-minute intervals, with a one-hour resting period in between. This step ensures a uniform mixture. Once properly blended, the suspension is left to dry under a fume hood for at least 24 hours, allowing complete evaporation of the solvent.

<sup>1</sup>The VWR® Symphony™ ultrasonic cleaner was used for this step.

The microthermite mixture is loaded into glass capillaries with inner diameters varying from 1.5 mm to 5 mm and an approximate length of 90 mm. To determine the fill volume, the precise inner diameter and length of each sample are measured beforehand. The filling process is carried out in stages, alternating between adding thermite and applying compressive force to enhance packing density. After drying, the nanothermite mixtures are packed into capillaries with an inner diameter of 1.5 mm and length of 10 mm. Both micrometric and nanometric sample length and mass are then measured to determine their packing densities.

### 2.3 Experimental Procedure

The ignition threshold (power-energy envelope) is examined. Both laser power and pulse duration are systematically adjusted to control the total energy deposited to the thermite sample. Prior to introducing the sample, pulse energy is recorded using the power meter's "single shot energy" mode under the specified laser power parameters. The power meter is then removed before testing begins. The thermite sample is positioned at the lens's focal point, and ignition and propagation behavior are captured through high-speed videography. The laser power is adjustable from 300 W to 3 kW, while pulse durations range from 0.5 ms to 10 ms. The study evaluates total energy input into the thermite samples, reaching up to 30 J.

While the laser has a minimum power output, reducing the sample's exposure can be achieved by moving it off axis. As the beam diverges, energy density decreases, diminishing the effective energy deposited into the system. To quantify the actual energy imparted to the thermite sample, a power meter is employed, with precautions taken to obstruct any portion of the beam that extends beyond the sample capillary's cross-sectional area.

High-speed videography is employed to measure the speed of flame propagation. To achieve this, samples are ignited, and the time taken for combustion to fully travel the length of the sample is recorded. By comparing this duration to the sample's measured length, both the average ignition time and overall propagation velocity are determined. To assess the minimum diameter required for sustained propagation, samples of different diameters are subjected to identical laser power and pulse width settings. Additionally, the dependence of flame propagation speed on sample diameter is analyzed.

## 3 Results

### 3.1 Preliminary power-energy threshold experiments

Preliminary ignition threshold experiments have been conducted on both micrometric and nanometric scale mixtures. Micron-scale tests were performed in nominal 3-mm-diameter capillaries, while the nanometric tests were performed in nominal 1.5-mm-diameter capillaries. The samples were placed at the focal point, and visual confirmation of ignition was received through high-speed videography. Figure 2 presents the preliminary power-energy threshold data collected for the micrometric scale and nanometric scale thermites. A distinct lower boundary was observed in the case of the microthermites, but the limits of the power and pulse width ranges of the laser pose significant challenges in doing so for the nanometric samples. Figure 2a demonstrates this phenomenon, in which the laser's minimum pulsewidth setting deposits enough energy for the sample to ignite at power values above 30 W. Thus, the experiment cannot conclusively determine at what energy value the sample initially ignites. Modifications to the experimental setup are in progress to address this challenge.

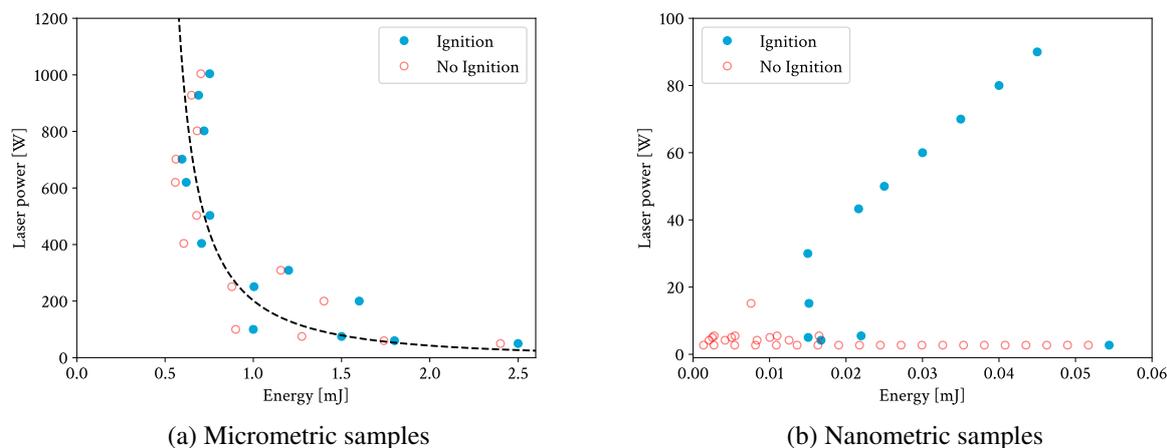


Figure 2: Laser power-energy threshold data for micrometric and nanometric samples

### 3.2 Preliminary flame propagation experiments

Preliminary flame propagation experiments were also conducted on the microthermites. The samples were packed into 1.5 mm, 1.75 mm, 2.13 mm, and 3.52 mm diameter capillaries, which were then placed at the focal point of the laser. Visual confirmation of ignition and flame propagation velocity data was collected via high-speed videography. Preliminary data shows that the samples undergo two distinct phases, the initial ignition phase, in which the flame propagation speed is significantly higher ( $\approx 0.6\text{--}1.75\text{ m s}^{-1}$ ), and the stabilization stage, in which the flame propagation speed significantly decreases ( $\approx 0.035\text{--}0.041\text{ m s}^{-1}$ ), and stabilizes for the duration of the sample length. Figure 3 demonstrates high-speed frames of a propagation event, where Fig. 3a illustrates initial ignition and Fig. 3b displays the flame approximately halfway through the length of the sample.



(a) Initial ignition



(b) Propagation halfway through sample length

Figure 3: Stills from high-speed videography of flame propagation event

## 4 Conclusion

Laser ignition of thermites has gained considerable attention as an innovative approach for initiating energetic materials, primarily due to the safety and logistical advantages provided by using a laser to trigger the heat release of the thermite reaction. This study explores the combustion properties of aluminum-molybdenum-trioxide (2Al + MoO<sub>3</sub>) systems with variable particle sizes, focusing on their response to varying laser power and energy levels. Initial experiments have identified the lower power thresholds below which propagation fails to occur. Additionally, preliminary measurements of flame velocity for the nanometric-sized system have been obtained.

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