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LOW-POWER LASER IGNITION OF ALUMINUM/METAL OXIDE NANOTHERMITES

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In this study, three different types of nanothermites, i.e., Al/CuO, MoO_3, and Al/Bi_2O_3, were produced using the widely spread wet (i.e., isopropanol based) method. In addition to the above method, the three nanothermites were also produced using a Resodyn LabRAM mixer. A paraffin-coated spherical Al nanopowder (100 nm) was used as the fuel source, while the oxidizers were nanometric powders of CuO (40 nm), MoO_3 (100 nm), and Bi_2O_3 (200 nm). The effect of nanothermite composition on the sensitivity for the tests of electrostatic discharge (ESD), impact, and friction was investigated. Scanning electron microscopy (SEM) was used to analyze the morphology and homogeneity of the nanothermites. Next, the nanothermites were thermally analyzed in terms of energy release, ignition temperature, and flame temperature using a thermogravimetric analysis differential and scanning calorimetry (TGA/DSC) technique. A low-power diode laser was used to evaluate the ability of different laser wavelengths (661, 532, and 445 nm) to produce the ignition energy needed for a specific thermite reaction. Low ignition delays (less than 15 ms) were obtained at approximately 300 mW laser power output for both Al/MoO_3 and Al/Bi_2O_3 thermites. Finally, a forward-looking infrared camera was used to estimate the ignition and burning temperatures of the Al/MoO_3 nanothermite.

KEY WORDS: *Al/metal oxide nanothermites, low-power laser, ignition, sensitivity tests, LabRAM mixer*

1. INTRODUCTION

Nanothermites can be considered for a wide range of energetic materials applications, mostly due to the wide spectrum of physicochemical properties obtained when changing their composition. Many of these applications arise directly from their high-energy density characteristics, leading to applications such as microscale propulsion and nanoscale welding. One interesting application is potential use as ammunition primers that can be ignited electrically or by low-energy laser irradiation. Traditional primers contain lead compounds such as lead azide and lead styphnate which are toxic to both user and the environment. The use of nontoxic nanothermites in this context would also be beneficial as a substitute for the various formulations containing lead or other toxic substances.

In a thermite type reaction, a metal oxide is the oxidizer and, generally, the fuel is aluminum. The nanothermites are generally composed of aluminum and metal oxide nanopowders, unlike conventional thermites, which are composed of micrometer-sized powders. The rate of release of energy in conventional thermite is relatively slow in comparison with conventional energetic materials. The typical combustion front propagation velocity in a condensed phase is of the order of several centimeters to a few meters per second [1]. It was shown [2] that a significant reduction in the particle size of the reactants (aluminum and metal oxide) leads to an important increase in the burning rate, up to explosive behavior.

The thermite reaction between aluminum and a metal oxide leads to the formation of aluminum oxide and metal with release of energy (ΔH):

$$M_xO_y + Al \rightarrow M + Al_2O_3 + \Delta H \tag{1}$$

Table 1 shows several thermodynamic properties of some of the most studied nanothermites: theoretical maximum density (TMD), heat of reaction, amount of gas produced, and the adiabatic reaction temperature [3].

Mixtures of aluminum and metal oxide are stable up to their ignition temperature at which point self-propagating high-temperature synthesis takes place and the thermodynamic products of alumina (Al_2O_3) and metal are formed. Several models suggest that the melting point of nanoparticles is significantly reduced, up to 300 K lower, when compared with the micrometric material and use this as an explanation for the behavior differences between thermites with different particle size. Consequently, this may have a major impact on the ignition temperature of the thermite. For example, a thermite containing 100 nm MoO_3 and 10–14 μm aluminum exhibits an ignition temperature of 955°C, while a mixture composed of the same MoO_3 and 40 nm aluminum shows an ignition temperature of 458°C [2]. It is believed that the homogeneity of mixtures of

TABLE 1: Thermodynamic properties of selected thermite reactions [3]

Thermite reaction	ρ_{TMD} [g/cm^3]	Q [cal/g]	Q [cal/cm^3]	**Gas generation @ 1 atm** [g gas/g mixture]	T_{ad} [K]
$2Al + Fe_2O_3 \rightarrow 2Fe + Al_2O_3$	4.175	945.4	3947	0.0784	3135
$2Al + Bi_2O_3 \rightarrow 2Bi + Al_2O_3$	7.188	505.1	3638	0.894	3319
$2Al + MoO_3 \rightarrow Mo + Al_2O_3$	3.808	1124	4279	0.2473	3688
$2Al + WO_3 \rightarrow W + Al_2O_3$	5.458	696.4	3801	0.1463	3253
$2Al + 3CuO \rightarrow 3Cu + Al_2O_3$	5.109	974.1	4976	0.3431	2843

nanoscale particles is higher and also the surface-to-volume ratio increases considerably at nanoscale level, allowing more of the aluminum to be in contact with the metal oxide. Since the thermite reaction is partially controlled by oxygen diffusion from the oxide to the aluminum, increasing the amount of aluminum in contact with the metal oxide reduces the diffusion distance and increases the rate of reaction.

Thermite compositions are generally achieved by mixing powders of metallic oxide and aluminum in a specific mass ratio. The variation in the aluminum/metal oxide composition is reported in terms of equivalence ratio (ϕ):

$$\phi = (F/A)_{Act}/(F/A)_{St} \tag{2}$$

In this equation, F represents fuel (Al), A is the oxidizer (metal oxide), and the subscripts Act and St indicate the actual and stoichiometric ratios. This equation considers the actual active Al content. It is understood that $\phi < 1$ corresponds to fuel lean mixtures, $\phi > 1$ are fuel rich, and $\phi = 1$ are stoichiometric.

In this paper, the preparation of various nanothermite mixtures and the results of sensitivity to electrostatic discharge (ESD), to impact, and to friction along with preliminary laser ignition results are reported.

2. EXPERIMENTAL

2.1 Materials

The characteristics and performances of a thermite are closely related to the type of metal oxides and aluminum nanopowders, their geometric shapes (sphere, pellet), their dimensions, the equivalence ratio, and the homogeneity of the mixture. For this project, the equivalence ratio was set at $\phi = 1.2$, which is a slightly fuel rich mixture. This choice reflects the recent literature where the value of 1.2 seems to be an optimal value for certain characteristics of nanothermites such as short delay of ignition and fast burning rate [2].

The type of aluminum that has been selected for the mixtures was ALEX-type aluminum nanopowder, coated with palmitic acid, and was obtained from Reactive Energetics (Quebec, Canada). The average particle size is approximately 100 nm. Single particles have the average size of 70–150 nanometers and form micro-agglomerates. The bulk density was about 0.32–0.37 g/cm^3, while the BET specific surface area was 12 m^2/g.

Whichever the type of aluminum used, the value of active aluminum content must be known. In fact, aluminum is always covered with a layer of aluminum oxide (Al_2O_3), and may also be covered with additional organic coatings. The determination of the active aluminum content was obtained by volumetric analysis based on the following chemical reaction:

$$2Al + 2NaOH + 2H_2O \rightarrow 3H_2 + 2NaAlO_2 \tag{3}$$

In carrying out the reaction in a fixed volume, the pressure change will be proportional to the amount of hydrogen released and itself proportional to the amount of active aluminum. One of the advantages of this method is the fact that it is insensitive to the type of coating layer surrounding the Al particle [1]. The result obtained for the active aluminum content of the Al powder used in this project was 87.9%, which is consistent with the specifications of the supplier.

Among the different types of metal oxide nanopowders available, copper oxide (CuO), molybdenum oxide (MoO_3), and bismuth oxide (Bi_2O_3) were selected. Shape and dimensions (as advertised by the seller) of the metal oxide nanopowders obtained from SkySpring Nanomaterials, Inc. (Houston, TX) are shown in Table 2.

2.2 Preparation of Nanothermites via the Wet Method

The first mixtures were prepared according to a widely used wet method [1–9], which involves mixing in a container the metal oxide and aluminum nanopowders in an inert solvent and placing the container in an ultrasonic bath for several minutes to ensure the homogeneity of the mixture. Thereafter, the mixture was left in a fume hood to allow the solvent to evaporate. This method is simple, but requires the use of flammable and volatile solvents such as hexane or isopropanol. In addition, when the mixture was dry, the surface layer tended to form aggregates that were some hour difficult to break, taking into account the sensitivity of nanothermites to friction.

Depending on the thermite to-be-synthesized, first the copper oxide (250 mg), the molybdenum oxide (200 mg), or the bismuth oxide (250 mg) was placed in a glass tube. Hexane was then added (5.4–6.2 mL) and the mixture was sonicated for 1 min to soak the oxide powder with the solvent. Nanometric Al-ALEX (87.8 mg, 116 mg, or 45 mg for, respectively, Al/CuO, Al/MoO_3, or Al/Bi_2O_3 nanothermites) with an active content of 87.9% was added to the oxide/hexane mixture and the suspension was sonicated for another 30 min. Temperature of water in the ultrasonic bath rose from 20°C to 35°C in that period of time. After sonication, the suspension appeared as a uniform slurry and was poured in a conductive container. The container was placed in a grounded metal drying pan in a fume hood until constant weight. Next, the dry powder was gently scraped from the walls of the conductive container; the container sealed, and then put in an appropriate storage place.

TABLE 2: Shape and dimension of nanopowders used

Metal oxide	Shape	Average particle size (nm)
Al	Spherical	100
CuO	Spherical	40
MoO_3	Spherical	100
Bi_2O_3	Spherical	<200

The yield of recovery for the Al/CuO nanothermite was 301 mg (97%), for the Al/MoO_3 nanothermite 263 mg (83%), and for the Al/Bi_2O_3 nanothermite 263 mg (83%). Losses were mainly caused by the powder that remained stuck to the walls of the glass tube during sonication. Visually, the resulting Al/CuO nanopowder was dark gray, as was the Al/MoO_3 nanopowder, while the Al/Bi_2O_3 nanopowder was greenish-gray.

2.3 Preparation of Nanothermites via the Dry Method

A second method was subsequently used and does not involve the use of any solvent. A LabRAM mixer (Resodyn Acoustic Mixers, Inc.) was used, which can mix powders of different nature using low-frequency, high-intensity acoustic energy, creating a uniform shear field throughout the entire mixing container (Fig. 1). Since nanothermites are extremely sensitive to electrostatic discharge (ESD), the conductive container was grounded in order to prevent the accumulation of static electricity.

Depending on the thermite to be synthesized, either CuO (250 mg) and Al-ALEX (87.8 mg) for the Al/CuO nanothermite, or MoO_3 (250 mg) and Al-ALEX (146 mg) for Al/MoO_3 nanothermite, or Bi_2O_3 (250 mg) and Al-ALEX (45 mg) for the Al/Bi_2O_3 nanothermite were placed in the conductive container. The container, held with a metal hose clamp that connected the system to ground (Fig. 1), was placed in the LabRAM mixer, grounded, and the mixing rate was set as follows: 10% intensity for a period of 10 s and at 30% intensity for 30 s. This cycle was repeated 4–5 times. The mixing procedure was done remotely. All resulting nanothermites appeared visually homogeneous and were placed in a conductive container and then stored.

FIG. 1: Left: Picture of the mixer used for nanothermites preparation; Right: Conductive bottle with stopper and hose clamp.

3. RESULTS AND DISCUSSION

3.1 Impact, Friction, and Electrostatic Discharge Sensitivity Tests

Nanothermites are primary explosives and as such require special attention during manipulation. As a general rule, the smaller the particle size, the higher the sensitivity of thermite mixtures to impact and friction. Thermite mixtures at the microscopic level are generally not very sensitive to impact and friction, but at nanoscale, thermites can be very sensitive to either stimuli or one of the two depending on the nature of the metal oxide in the mixture.

Although the increased sensitivity can make the handling of nanothermites more dangerous, increased sensitivity to impact and friction can be beneficial in certain applications such as percussion igniters. However, some thermites also have increased sensitivity to ESD, which has limited practical application and therefore becomes a safety hazard. For example, from literature the thermite composed of 40 nm Bi_2O_3 and 40 nm Al was shown to have a very high sensitivity to ESD and was able to ignite with an energy as low as 0.125 μJ [1]. This energy level is well below what a human body can store, making the handling of these energetic materials very hazardous.

The results for sensitivity to impact, friction, and ESD for all tested thermites are shown in Table 3. From the sensitivity to impact results, one can notice that all three nanothermites were insensitive to this stimulus, the value obtained being higher than 80 J.

On the contrary, the results for the sensitivity to friction are very different. For example, the Al/CuO nanothermite showed ignition by friction 360 N and was considered therefore not very sensitive to this stimulus. One could observe on the ceramic plate and sample holder, the reddish color of metallic copper produced by the reaction (Fig. 2, Left side). Differently, the Al/MoO_3 nanothermite can be considered to be moderately sensitive to friction since ignition reaction occurred at 160 N. Finally, the Al/Bi_2O_3 nanothermite is by far the most sensitive with observed ignition reaction, accompanied by loud noise, at A value below 5 N and more probably closer to 1 N, which makes this nanothermite very sensitive to friction.

Results for sensitivity to ESD were performed in an open cell. For the Al/CuO nanothermite, ignition occurs at a measured energy of 0.056 J. As was the case for the

TABLE 3: Summary of the results for sensitivity to impact, friction, and ESD for the tested nanothermites

Nanothermite	**Impact**	**Friction**	**ESD**
	J	N	mJ
Al/CuO	>80	360	56
Al/MoO_3	>80	160	<1.5
Al/Bi_2O_3	>80	<5	<1.5

FIG. 2: Left: Ceramic plate of the friction sensitivity test after reaction with Al/CuO nanothermite; Right: Setup for ESD test after ignition of Al/CuO nanothermite.

sensitivity to friction test, one can observe the reddish metallic copper formed on the sample holder and needle during the reaction (Fig. 2, right side).

The other two nanothermites, Al/MoO_3 and Al/Bi_2O_3, were found to be much more sensitive to ESD. By adjusting the voltage to the lowest value possible for the equipment used (3 kV, corresponding to an energy of 1.5 mJ), an ignition reaction occurred for both nanothermites. In addition, as previously for the sensitivity to friction test, the Al/Bi_2O_3 nanothermite reacted violently and noisily to the ESD test and even broke the sample support into several pieces (Fig. 3). One possible explanation for this behavior is related to the observed higher amount of gas generated by the Al/Bi_2O_3 reaction when compared to the other thermites tested in this work, but other phenomena might also contribute to this behavior.

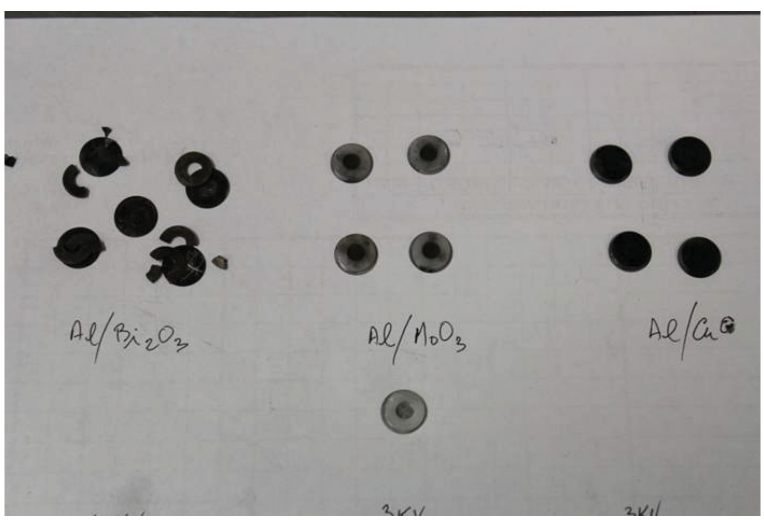

FIG. 3: Sample holder after reaction to ESD for the Al/Bi_2O_3 nanothermite.

3.2 TGA/DSC and SEM/EDS Analysis

Figure 4 shows the thermogravimetric analysis/differential scan calorimetry (TGA/DSC) analysis of the Al/CuO nanothermite. From the DSC curb, the endotherm at 655°C can be attributed to the melting of nano Al particles (fuel rich mixture), while the exotherm at 744°C is believed to be caused by the thermite reaction between the Al and the CuO. The observed difference between the two recorded temperatures is somewhat unusual and a more thorough investigation (for example by varying the rate of temperature increase during the TGA/DSC analysis) is required in order to clarify this point.

Figure 5 shows the TGA/DSC analysis of the Al/Bi_2O_3 nanothermite. From the DSC curb, the endotherm at 654°C can be attributed to the melting of nano Al particles (fuel rich mixture), while the endotherm at 735°C is believed to be caused by the decomposition of the Bi_2O_3 oxide. The thermite reaction between the Al and the Bi_2O_3 is the cause of the observed exotherm at 813°C, and this reaction is sensibly more violent for this thermite when compared to the Al/CuO thermite (Fig. 4).

Figure 6 shows a DSC analysis where the two methods of synthesis were compared for the Al/MoO_3 thermite. As can be noticed, there is virtually no influence of the type of synthesis method on the reactivity of the thermite. For both curbs, the exotherm at 556°C can be attributed to the thermite reaction between the Al and the MoO_3 while the endotherm at 657°C is probably caused by the melting of the remaining nano Al particles (this was also a fuel rich mixture).

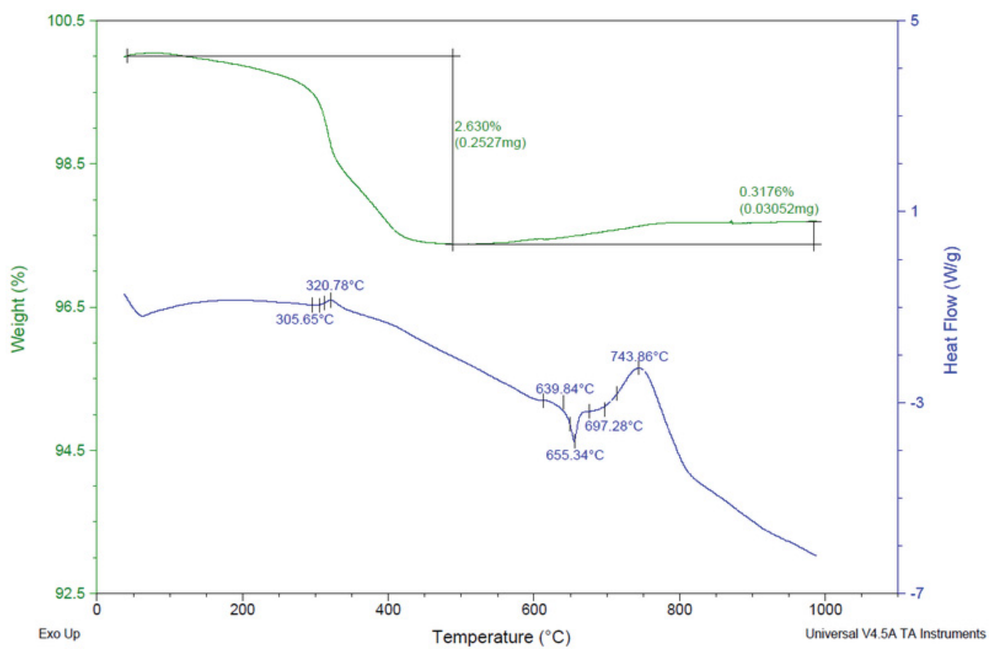

FIG. 4: TGA/DSC analysis of the Al/CuO nanothermite.

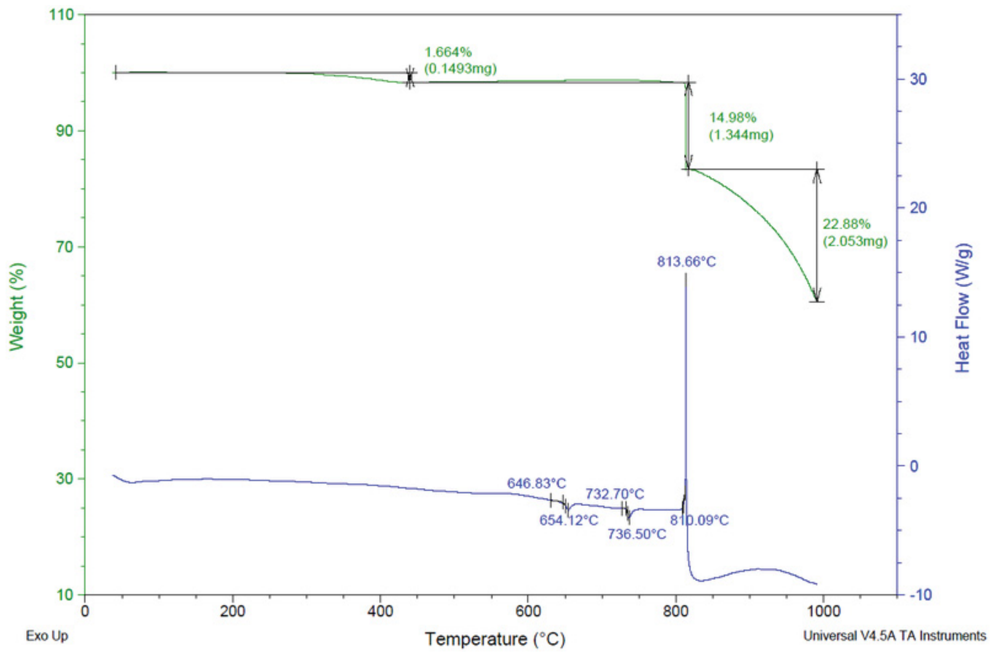

FIG. 5: TGA/DSC analysis of the Al/Bi_2O_3 nanothermite.

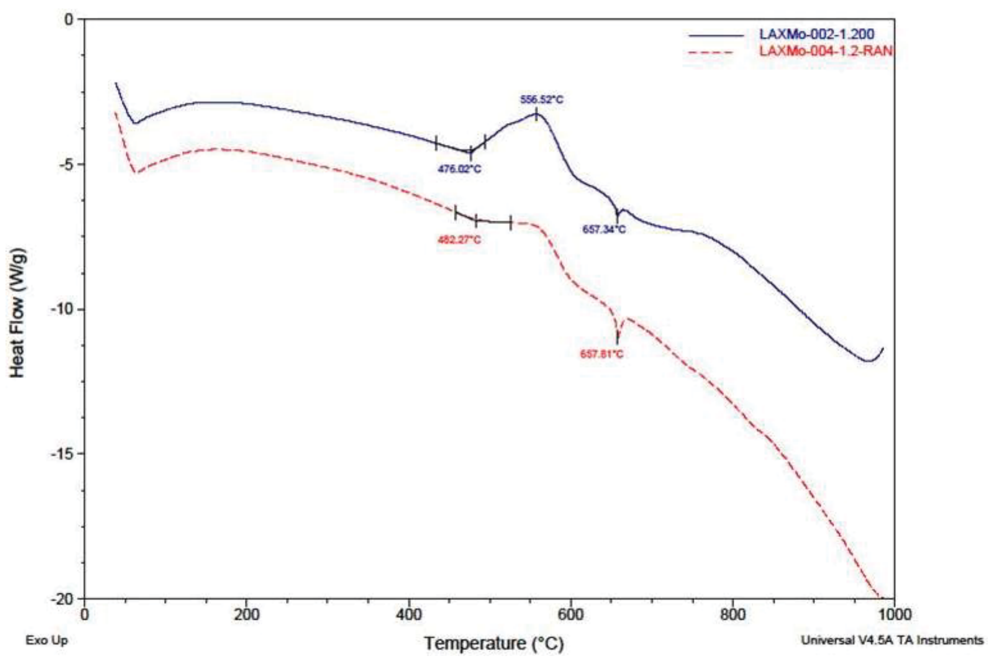

FIG. 6: DSC analysis of the Al/MoO_3 nanothermite: overlay of the wet and dry synthesis methods.

Figure 7 shows an example of scanning electron microscopy (SEM) analysis, in this particular case for the Al/CuO nanothermite. As expected from the manufacturer specifications, the Al particles were spherical and had an average diameter of 100 nm. On the contrary, the size and shape of CuO particles were very far from the manufacturer specifications. In fact, the manufacturer specifications said that the CuO particles should be spherical and should be around 40 nm in diameter, while the SEM analysis revealed micrometer-size nonspherical particles (Fig. 7).

The above observations were also confirmed by the energy-dispersive X-ray spectroscopy (EDS) analysis (Fig. 8), where it is easy to observe the important size and shape differences between the Al (red) and CuO particles (light blue). An important difference between the specifications and the reality was also found, to a lesser extent, for the other two metal oxides used in this study (data not shown). Although the metal-oxide particles' size/shape difference between the *theory* and the *reality* is quite important, it did not affect the purpose of this work as the resulting materials were found to be very reactive when ignited with a low-power laser, as shown in the next section. The influence of the particle size and shape on the ignitability of the thermites by low-power lasers will be investigated in a future study.

3.3 Laser Ignition Tests

One of the main objectives of this preliminary study was to test if the aluminum-based nanothermites could be ignited by irradiation with low-power laser. The three nanothermites Al/CuO, Al/MoO_3, and Al/Bi_2O_3 were submitted to some specific laser ignition tests. Table 4 shows the main characteristics of the three lasers used in this study.

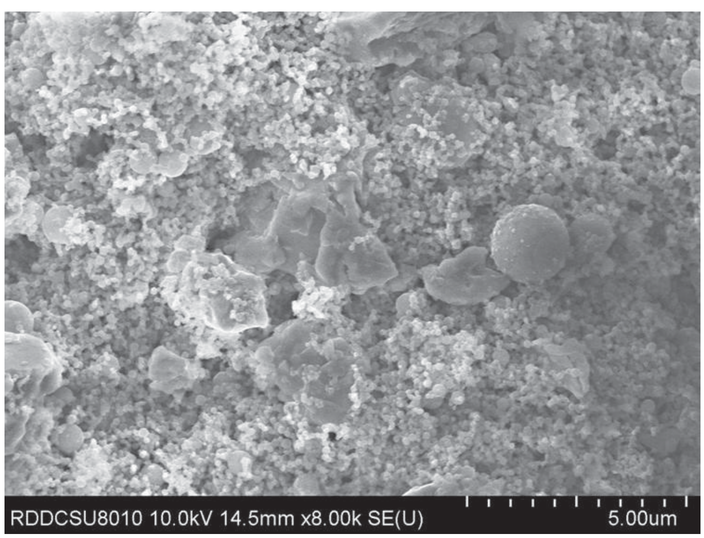

FIG. 7: SEM image of the Al/MoO_3 nanothermite.

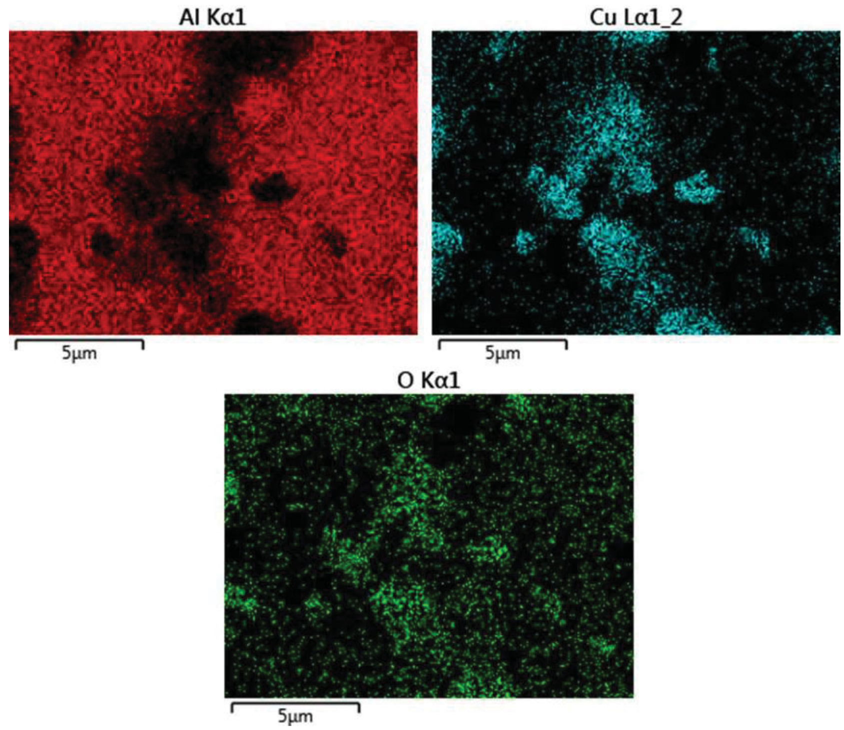

FIG. 8: EDS analysis of the Al/MoO_3 nanothermite.

TABLE 4: Main characteristics of the different lasers used in this study. A and B are beam sizes at the waist

	Wavelength [nm]	**Max power [W]**	A (1/e) **[mm]**	B (1/e) **[mm]**	**Power density [W/cm^2]**
November (Blue)	445	2.15	1.27	1.13	149
Mike (Green)	532	0.54	0.78	0.57	121
Golf (Red)	661	0.22	2.76	1.98	4

Some preliminary tests showed that the green laser (Mike) was not very stable, so it was discarded from future tests. The other two lasers were much more stable and their power varied linearly with the applied current. Between the two, the blue laser (November) was preferred due to its greater power and smaller beam size. Figure 9 shows an example of the laser ignition of Al/MoO_3 nanothermite with the blue laser (445 nm) at an output of 150 mW. The spectrum was recorded using a high-speed silicon DC detector (DET110), which had UV to near-IR sensitivity and was linked to an UV spectrometer. Relatively rapid ignition can be observed for this nanothermite, with a measured ignition delay time of 0.036 s. The ignition delay was measured by measuring the time lap between the

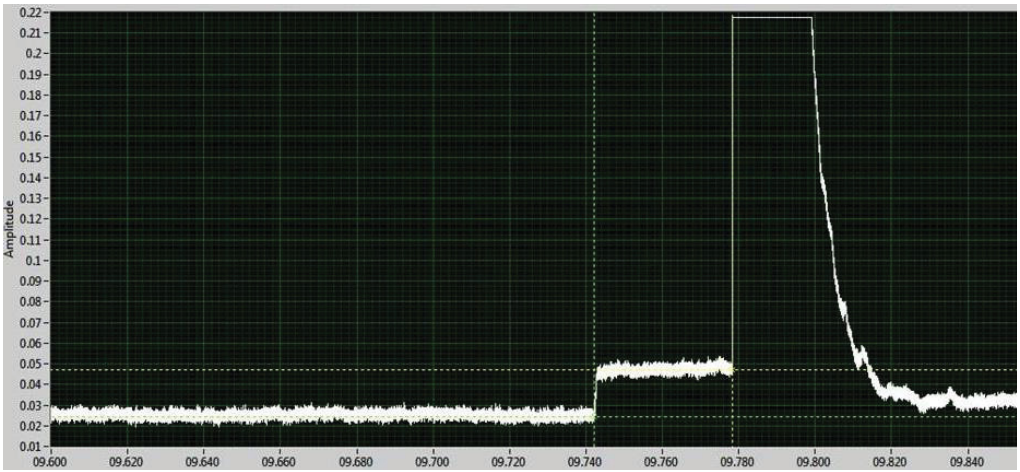

FIG. 9: Example of laser ignition of Al/MoO_3 nanothermite with ignition delay of 36 ms.

moment when the laser was activated (power on) and the moment when an important amplitude change was noted on the high-speed silicon DC detector.

Figure 10 resumes the different laser ignition tests performed for the three nanothermites. These results are only preliminary, but overall they are very interesting and show the great potential of aluminum-based nanothermites for use as igniters for various propulsion applications. One can observe from Fig. 10 that a generally considered as acceptable ignition delay, i.e., less than 0.0l5 s, requires approximately 300 mW for both the Al/MoO_3 and the Al/Bi_2O_3 thermites. On the contrary, the Al/CuO thermite appears

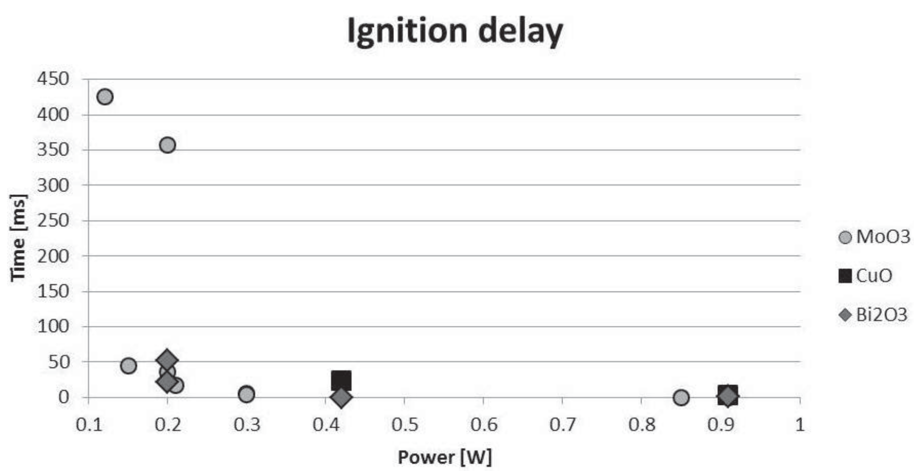

FIG. 10: Ignition delays for the preliminary tests with the 445 nm laser (blue). The ignition delays at laser power values greater than 1 W were omitted.

to be slightly less sensitive than the other two, but due to the previous SEM/EDS observations for the CuO particles, more tests are required in order to confirm this hypothesis.

3.4 Burning Rate (BR) and Reaction Temperature Estimation

To measure the burning rate of the thermites in a semi-confined setup, a 23 cm boronsilicate Pasteur pipette was used (Fig. 11). The small diameter tip-end of the pipette was closed by melting it with a propane flame, while the large diameter end was left open. Around 4.5 cm, measured from the tip-end, it was filled with the thermite mixture using a small spatula and then carefully taped on its side to gravity-compact the thermite. The thermite was then laser-ignited through the glass and the process was filmed using a high-speed camera. The high-speed camera frame rate was 91,742 fps, which corresponds to approximately l.09E-5 seconds per frame. To estimate the BR, a paper ruler was place behind the pipette (see Fig. 11), with each millimeter and centimeter on the ruler alternating between black and white colors.

Figure 12 shows the combustion of the Al/MoO_3 nanothermite, recorded at every frame of the high-speed camera. From Fig. 12 it can be seen that the thermite combustion was very uniform (no dark spots on the pipette white line). The estimated (by calculating the time on the high-speed camera record) BR was calculated to be approximately 743 m/s. In comparison, the BR of the Al/CuO thermite, measured in similar conditions, was estimated to be 134 m/s, with the combustion being less uniform (data not shown).

The BR value measured for the Al/MoO_3 thermite is relatively quick but sensibly lower than other literature values [9]. The differences between the present work BR values and other literature values were to be expected as there are significant differences between the experimental setup used. Among others, the present experiment measured the combustion speed of semi-confined and virtually uncompressed powder thermite, with both factors significantly affecting the speed of combustion.

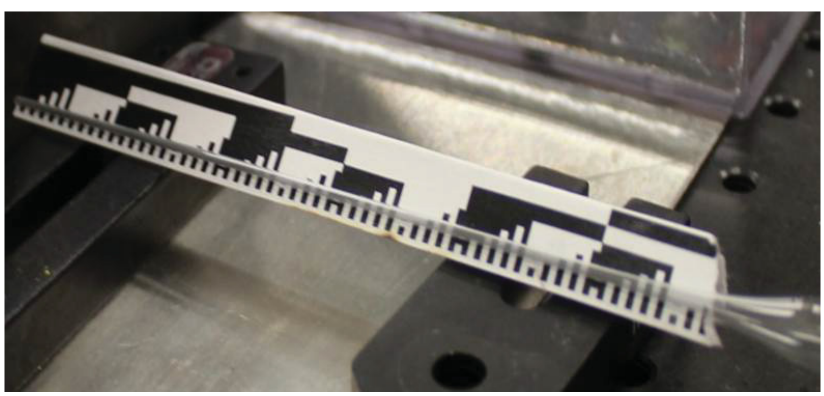

FIG. 11: View of the Pasteur pipette with 3.8 cm of Al/MoO_3 thermite in front of a paper ruler. The blue arrow shows approximately where the laser beaus hit the pipette.

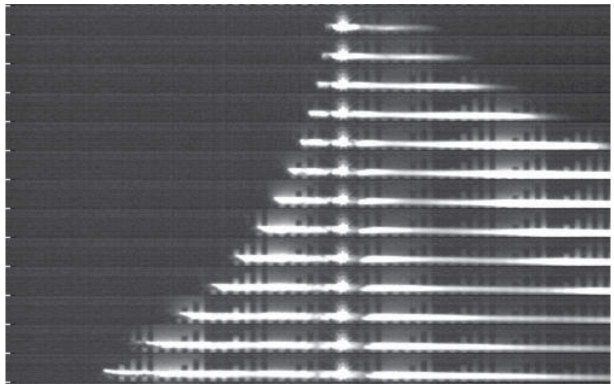

FIG. 12: Al/MoO_3 nanothermite combustion in Pasteur pipette, recorded at every frame. The blue line shows where the laser hit the pipette.

Finally, a forward looking infrared (FLIR) Orion SC7600 camera was used to estimate the ignition and burning temperatures of the Al/MoO_3 nanothermite. Because of the relatively low maximum frame rate of the camera (800 fps, which corresponds to 1.25E-3 seconds per frame), the power of the laser had to be diminished as much as possible in order to have a measurable delay before ignition. Figure 13 shows the ignition of Al/MoO_3 thermite with a 120 mW blue laser, recorded at 697 fps. The temperature values shown on the scale on the right side of the figure are offset as no calibration of the FLIR camera was performed previous to the experiment. Despite the lack of an exact temperature reading, it can be visually noted that a very quick and uniform ignition was achieved. In addition, a significant difference (574°C) between the lowest and the highest temperature was recorded, which is very close to the value of the thermite reaction exotherm (556°C, Fig. 6) recorded during the TGA/DSC analyses of the same thermite.

4. CONCLUSIONS

In this study three different nanothermites, Al/CuO, Al/MoO_3, and Al/Bi_2O_3, were produced using both wet and dry synthesis methods. A paraffin-coated spherical Al nanopowder (100 nm) was used as the fuel source, while the oxidizers were nanometric spherical powders of CuO (40 nm), MoO_3 (100 nm), and Bi_2O_3 (200 nm). For the wet synthesis, the Al and the respective metallic oxide were placed in a glass tube containing hexane or isopropanol and then the mixture was sonicated for 30 min. After sonication, the mixture was placed in a conductive container and the solvent was allowed to evaporate at room temperature. When the dry method was used, the thermites were produced using specifically designed Resodyn LabRAM mixing equipment. Both methods produced comparable homogeneous mixtures. SEM was used to assess the morphology and the homogeneity of the mixture. The effects of nanothermite composition and stoichiometry on ESD, impact, and friction sensitivity were measured. A diode laser was

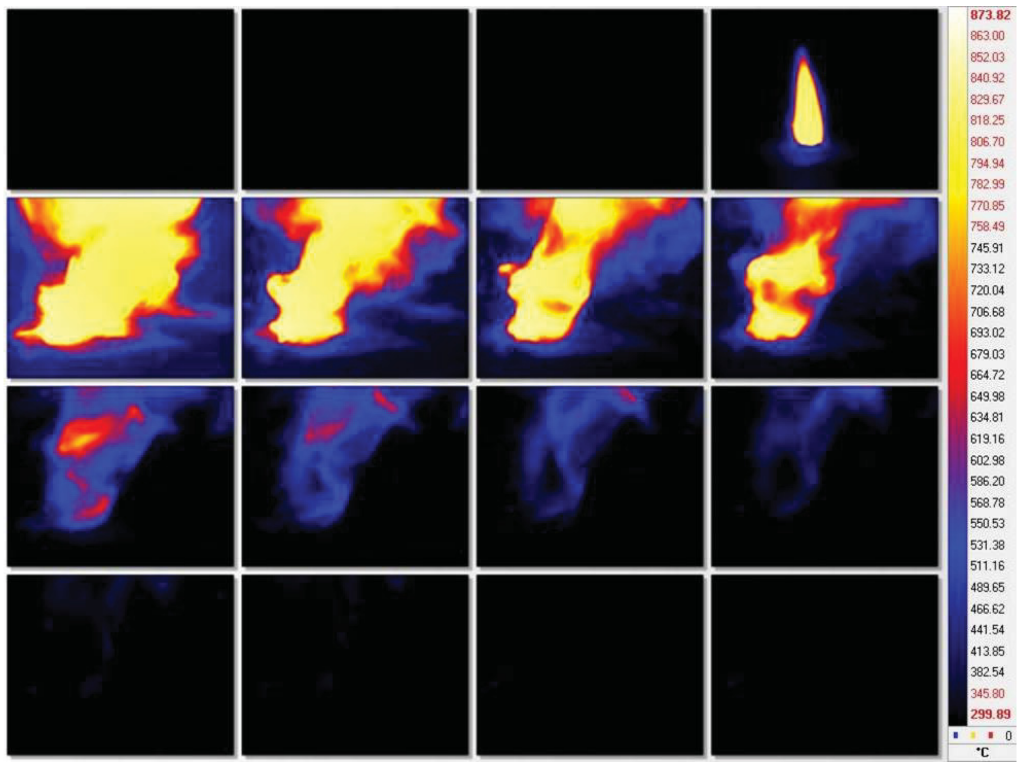

FIG. 13: Ignition of Al/MoO_3thermite with a 120 mW blue laser, recorded with a FLIR camera at 697 fps. The temperature values on the right scale are offset as no calibration of the camera was performed.

used to evaluate the influence of the laser wavelength (661, 532, and 445 nm) and power to produce the ignition energy needed for a specific thermite reaction. These results showed a great potential of aluminum-based nanothermites for use as igniters for various propulsion applications. Very good ignition delays, i.e., less than 15 ms, were obtained at approximately 300 mW laser power output for both the Al/MoO_3 and the Al/Bi_2O_3 thermites. The BR of the Al/MoO_3 nanothermite, measured in a Pasteur pipette, was found to be very uniform. The estimated BR was calculated to be approximately 743 m/s. In comparison, the BR of the Al/CuO thermite measured in similar conditions was estimated to be 134 m/s, with the combustion being less uniform (data not shown). Finally, a FLIR camera was used to estimate the ignition and burning temperatures of the Al/MoO_3 nanothermite. Despite the lack of an exact temperature reading, it was visually noted that a quick and uniform ignition was achieved. The temperature difference (574°C) between the lowest and the highest points was found to be very close to the value of the thermite reaction exotherm (556°C) recorded during the TGA/DSC analyses of the same thermite.

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REFERENCES

1. Puszynski, J. A., Bullian, C. J., and Swiatkiewicz, J. J., Processing and ignition characteristics of aluminum-bismuth trioxide nanothermite system, *J. Propuls. Power*, 23(4):698–706, 2007.
2. Pantoya, M. and Granier, J. J., Combustion behavior of highly energetic thermites: Nano versus micron composites, *Propellants, Explosives Pyrotech.*, 30(1):53–62, 2005.
3. Fischer, S. H. and Grubelich, M. C., A survey of combustible metals, thermites, and intermetallics for pyrotechnic applications, Report SAND-95-2448C, CONF-9607l7-4, *AIAA-JASME/SAE/ASEE Joint Propulsion Conf. and Exhibit*, Orlando, FL, 1996.
4. Wang, J., Hua, A., Persic, J., Wen, J. Z., and Zhou, Y. N., Thermal stability and reaction properties of passivated Al/CuO nano-thermite, *J. Phys. Chem. Solids*, 72:620–625, 2011.
5. Stamatis, D. and Dreizin, E. L., Thermal initiation of Al-MoO_3 nanocomposite materials prepared by different methods, *J. Propuls. Power*, 27(5):1079–1087, 2011.
6. Kappagantula, K. S., Farley, C., Pantoya, M. L., and Horn, J., Tuning energetic materials reactivity using surface functionalization of aluminum fuels, *J. Phys. Chem. C*, 116:24469–24475, 2012.
7. Foley, T., Pachero, A., Maichi, I., Yetter, R., and Higa, K., Development of nanothermite composites with variable electrostatic discharge ignition thresholds, *Propellants, Explosives Pyrotech.*, 32(6):431–434, 2007.
8. Moore, K., Pantoya, M. L., and Son, S. F., Combustion behaviors resulting from bimodal aluminum size distribution in thermites, *J. Propuls. Power*, 23(1):181–185, 2007.
9. Sanders, V. E., Asay, B. W., Foley, T. J., Tappan, B. C., Pacheco, A. N., and Son, S. F., Reaction propagation of four nanoscale energetic composites composites (Al/MoO_3, Al/WO_3,Al/CuO, and Bi_2O_3), *J. Propuls. Power*, 23(4):707–714, 2007.