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Assessing the Mixedness of Composite Solid Rocket Propellants Using Fluorescent Particles

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A new diagnostic technique was developed for assessing the effectiveness of mixing techniques of solid composite propellants using nanoparticle additives. The diagnostic uses nanosized quantum dots in suspension or micron-sized powders that are mixed into the propellant in place of the additives. Upon exposure to an ultraviolet light source, the particles fluoresce, hence serving as tracers to assess the uniformity of the mixture and therefore the effectiveness of the mixing procedure. Collection of the image using a digital camera provides data on intensity variations in the fluorescent signal, allowing for quantitative assessment of uniformity and mixedness. Various mixtures involving hydroxyl-terminated polybutadiene binder and ammonium perchlorate oxidizer were manufactured at various levels of mixing to test the diagnostic. In addition to confirming the uniformity of the nanosized particles using the target mixing procedure, variations in mixing quality and comparisons between mechanically and hand-mixed propellants showed distinct differences correlating to the mixedness of each propellant that was supported with data from burning rate studies. The present diagnostic can therefore also be used to assess the mixedness of propellants that do not contain nanoparticle additives. Other potential applications include curing agent dispersion assessment and linking homogeneity to mixedness and mechanical properties.

I. Introduction

ASSESSING the mixedness of a solid rocket propellant is commonly conducted through either nondestructive or destructive techniques. nondestructive techniques focus on testing without alteration of the sample, whereas destructive techniques revolve around testing the limits of the propellant. nondestructive analysis usually includes visual inspections, x-ray testing or ultrasonic testing of entire propellant grains [1]. Visual inspections are conducted to identify internal cavities (bubbles), cracking, or surface irregularities on or in the propellant. X-ray and ultrasonic testing allows for internal investigation of the propellant but are expensive processes with limitations placed on the ability to see beyond nonbonded interfaces, such as propellant–propellant boundaries. Destructive techniques use batches of identical propellants to examine ballistic and mechanical properties and may include tensile strength tests and chemical analysis of small portions of propellant [1,2]. Additionally, the repeatability of burning rate data confirms the predictability of the mixedness of a propellant [3]. Although the batch-to-batch statistical variation can be obtained or verified with such techniques, the actual dispersion of specific particles within the matrix is not routinely measured.

Of particular interest to the present study is the use of small quantities (typically less than a few percent of the entire propellant mixture by mass) of nanosized additives to tailor the burning rate of composite rocket propellants [4]. The size range of these particles is typically on the order of 5–20 nm. Uniformly distributing the nanoparticles within the propellant mixture is critical to effectively take advantage of the unique properties of the nanoparticles, such as their high surface-to-volume ratios and their often-unique surface reactivities. One method to uniformly mix the nanosized additives into a composite propellant that has been demonstrated in the authors' laboratory involves the use of a liquid suspension containing the particles. This liquid is mixed directly with the binder and solid oxidizer, and in a later step the volatile liquid is evaporated, leaving the propellant ingredients intimately mixed with the nanoparticle additive [4]. The ability to visually assess the effectiveness of such a mixing technique was the original goal of the new diagnostic presented in the current study.

Although detailed information on the distribution of ingredients can be obtained from scanning electronic microscopy [5–7], such a technique requires special preparation of the samples and may not be practical for assessing actual propellant mixtures. Scanning electronic microscopy also cannot resolve the full range of size scales from nanosized additives to micron-sized oxidizer particles in a single image. The fluorescing diagnostic tool developed and presented herein by the authors is a new nondestructive tool for characterizing the mixedness of a propellant containing nanoparticles that may also allow for the analysis of the spatial distribution of the primary ingredients within a solid propellant matrix.

In developing the new propellant diagnostic, we first researched the viability of using fluorescing micron and nanoparticles within our propellants. Details of the diagnostic and a demonstration of the technique are presented in this paper. Following a brief background on the fluorescing particles, the experimental setup and mixing techniques are described. Results in the form of photographic images and intensity distribution plots are provided.

II. Background

From basic physics, fluorescence is defined as a luminescent light, and heat is not the motivating factor in its generation. Rather, a

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Table 1 Characteristics and specifications of the micron- and nanosized particles used herein

	Nano particle	Micron particle
Manufacturer	Molecular probes	MaxMax (distributor)
Fluorescing yield	1.0	1.0
Excitation wavelength	365 nm	365 nm
Emission wavelength	419 nm	617 nm
Average particle size	0.024 ± 0.004 μm	≈ 10 μm
State of matter	Suspension	Powder
Concentration	2.6×10^{15} particles/mL	——

high-energy photon, commonly in the ultraviolet (UV) portion of the spectrum, is absorbed by a material and a photon lower in energy, commonly in the visible portion of the spectrum, is emitted. Fluorescence yield is an extensive physical property based upon the number of fluorescing particles, the probability of absorbing a photon, and the probability of emitting a photon [8,9]. Fluorescence yield (Φ) is the relationship between the number of photons emitted compared with the number of photons absorbed by a material:

$$\Phi = \frac{\#\text{Photons Emitted}}{\#\text{Photons Absorbed}}$$

Materials with a fluorescing yield as low as 0.10 still have measurable fluorescing ability. Fluorescence from molecules and particles is commonly used in many areas of science and engineering as a tracer diagnostic, from biological applications to fluid mechanics flow visualization. The light source can range from a common, high-power lamp to a tunable dye laser. The fluorescing medium can come from a molecule or particle that is naturally occurring in the system of interest, or it can come from additives that possess the desired fluorescence characteristics.

Two highly fluorescing, relatively inert solid particles were chosen for the present investigation. Table 1 summarizes the source and physical characteristics of each particle. One tracer material was a blue-fluorescing nanoparticle or quantum dot, commonly used in biological tracer applications [10]. These quantum dots were stored in a liquid suspension as provided by the manufacturer, and the particles had a stated average size of 24 nm. The blue-fluorescing wavelength when excited at 365 nm is 419 nm for the quantum dots.

The second tracer additive was a red-fluorescing, micron-sized (10 μm) particle commonly used as a tracking device in crime prevention. They arrived and were stored as a dry powder. These micron-sized particles possessed the same excitation wavelength, 365 nm, as the quantum dots, so a single light source could be employed when using either material (see below). When excited at this UV wavelength, the red particles fluoresced at 617 nm.

III. Experiment

As mentioned above, the aim of the investigation was to incorporate quantum dots that act as optical tracers into a composite solid propellant in the same manner that burning rate-enhancing nanoparticles are added. Initial forays into the investigation focused on proving that a quantum dot could be effectively added into a solid propellant. This proof was accomplished by ruling out the fluorescing capability of the primary ingredients in a baseline propellant which had, nominally, 80% monomodal ammonium perchlorate (AP) (200 μm) and 20% binder by mass. The binder consisted of HTPB cured with isophorone diisocyanate (IPDI) in a 10.44:1 ratio. Next, the nanoparticles were substituted in place of a previously examined nanoparticle additive in a hand-mixed propellant [4,11]. Further details on the mixing methods are provided below.

Since nanoparticles are prone to agglomeration on small scales, a wet-mixing technique was used to limit the amount of agglomeration [4]. Typically, each measured ingredient is added to a mixing chamber, creating a slurry. After appropriate amounts of time mixing under a vacuum, the propellant is extruded and cured. Instead of adding the nanoparticle into the slurry as a dry powder, the wet-mixing technique introduced the nanoparticle while suspended in a solvent. An additional step was added to the normal mixing process to evaporate the volatile solvent before curing. Since the burning rate-enhancing additives may be added while in a suspension, adding the quantum dots, which are also in a suspension, was a natural method for recreating a propellant with tracers instead of burning rate enhancers. Figure 1 shows a cured propellant strand containing the quantum dots under normal lighting conditions and then when bathed in UV light. Note the visible uniformity of the light emission in the right-hand image, which is further elaborated on below.

An optical setup consisting of a Mercury arc lamp, select filters corresponding to excitation and emission wavelengths, neutral density filters, and a charge-coupled device (CCD) image-capturing device was designed, as seen in Fig. 2. The lamp was manufactured by Newport–Oriel, model number R-3139 and used a Newport–Oriel 100-W Mercury bulb, part No. 6281. The excitation filter was a Newport–Oriel 365-nm ($\pm$10 nm) narrow band filter, part No. 58650. The emission filters were narrow band filters ($\pm$10 nm) manufactured by Omega Filters, Inc. A 420-nm filter, part No. 20BPF10-420, was used for the blue-fluorescing quantum dots, and a 620-nm, part No. 10BPF10-620, filter was used for the red-fluorescing micron particles. Neutral density filters manufactured by Newport–Oriel, part numbers FSQ-0D30 and FSQ-07D0, were used to cut down on the amount of fluorescence captured.

A Canon Power Shot A-640 with 10 million effective pixels was attached to a computer and operated with Breeze Systems PSR Remote software. The images were analyzed with Efg's Computer Lab Pixel Profile analysis software, version 1024-1. The Pixel Profile analysis software generates a graph of pixel intensity values from two arbitrary points on an image. Graphs of red, green, and blue values or the derived values of collective intensity, hue, saturation and value can be created. All possible graphs were evaluated, and graphs documenting the blue pixel variations for the quantum dot experiments and red pixel variations for the micron-particle experiments were selected. Arbitrary units relating to red–green–blue intensity values demonstrate the inherent differences between each sample examined.

A. Mixing Variations

Propellant samples were made using both hand- and mechanical-mixing techniques [13]. Formula batches were created in 20-g samples. Ingredients were added to either a 250-mL beaker (hand mix) or a mixing bowl (mechanical mix) in a manner similar to industry standards for propellant creation [1,2]. Details of the two techniques as used in the authors' laboratory are provided in Stephens et al. [12,13], and a brief summary is provided herein. Hand mixes were made by blending the ingredients, minus the curing agent, for an

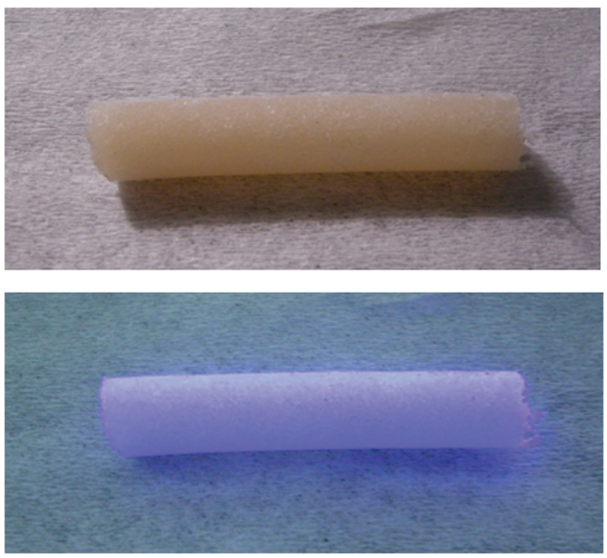


Fig. 1 Photograph of a quantum dot-laced propellant sample under normal (upper) and fluorescing (lower) lighting conditions.

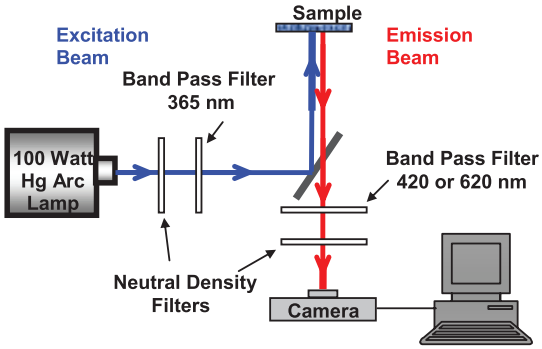


Fig. 2 Optical schematic for capturing CCD images of fluorescing particles.

allotted amount of time using a glass stirring rod. Before the curing agent (IPDI) was added, the mixture was degassed in a dessicator for two hours to remove air pockets and to remove the fluid from the particle/additive suspension.

Mechanical mixes have the advantage of being both under a vacuum and mixing the ingredients simultaneously, as well as being mixed for longer periods of time. For both styles of mixing (hand and mechanical), the curing agent was the last ingredient added, and the propellant was mixed for an additional amount of time before propellant strands were manufactured.

Propellant strands were created using 6.3-mm (0.25-in.) outside diameter Teflon tubing in a mechanical press method. The propellant was added to a plastic syringe, and the tubing was added to the nozzle end and a vacuum was pulled. The combination of the vacuum and the resistance from the plunger prevents the formation of air pockets in the propellant. One-inch (25-mm) sections were cut from the propellant-filled tubing and cured for one week at 55°C.

A variety of hand and mechanically mixed propellants containing fluorescing particles were created to examine several facets of the mixing techniques used in the authors' laboratory. The focus of the quantum dot investigations was on propellant mixedness and the distribution of nanosized additives in the mixture, which demonstrated the effectiveness of our hand-mixing technique. The fluorescing micron-particle investigations compared hand and mechanical mixes as well as evaluated particle distribution within a propellant. Further details on the two types of mixture studies are provided in the next two sections.

B. Propellant Mixedness

A gradation of hand-mixed propellants was created with the fluorescing nanoparticles. A 20-g sample of each propellant was mixed according to the following recipe by mass: 79% AP (oxidizer), 18% HTPB (binder), 1% fluorescing particle suspension, and 2% IPDI (curing agent). The actual mass of the additive was less than 1% due to water being the medium through which the quantum dot was in suspension. After the water was vacuumed off, the number of particles in the propellant was approximately 2.6×10^{15}. The poorly mixed propellant was created by adding all of the chemicals at the same time and mixing for (only) approximately 30 s. The intermediate mix was created by adding the chemicals in a manner representative of the hand-mix guidelines [12], but with a substantially shorter mixing time. Finally, a thoroughly mixed propellant was created in the usual fashion described above. In addition to curing propellant strands, small portions of propellant were spread on microscope slides to represent smears (thin layer) and smudges (thick layers). Cross sections, less than 2 mm thick, were cut from the strands to analyze the interior of the propellant samples.

C. Hand Versus Mechanical Mixing

Although earlier studies in the authors' laboratory indicated that there was little difference in burning rate between mixtures prepared with either hand or mechanical means [12], a series of tests was conducted using fluorescence tracers to see if there were any noticeable physical differences in mixedness between the two methods. This comparison was done using the micron-sized additive in powder form (Table 1).

The micron-particle mixes followed the guidelines for typical dry-mixed propellants manufactured in the authors' laboratory [4,12]. The main difference between the wet and dry mixes centers on the medium through which the additive is introduced. Wet mixes have the additive in a suspension/solution (as in the previous section), while the dry mixes use powdered additives. Dry mixes have the advantage of not having to remove the carrier medium through which wet-mix-additive propellants are created. Thoroughly mixed propellants were created to compare hand and mechanical-mixing techniques. Each propellant from both methods was composed of 79% AP, 18% HTPB, 1% tracer additive, and 2% IPDI by mass. The same formulas were used in the burning rate comparisons performed by Stephens et al. [12].

D. Trace Particle Distribution

Finally, an additional hand-mixed propellant was made where only a trace amount (less than 0.05% by mass) of fluorescing micron particles was added to look at the distribution and/or agglomeration of additive particles. This trace amount was also purposely added at the very end of the mixing process and was only superficially mixed in. The intent here was to intentionally induce nonuniformities in the distribution of the powdered additive. Propellant strands, strand cross sections, and microscope smear and smudge slides were prepared for subsequent analysis. The mix in this case was also composed of 80% AP and approximately 18% HTPB and 2% IPDI with the balance being the trace amount of the micron-sized particles.

IV. Results

A. Propellant Mixedness

As the mixing time increased, both qualitative and quantitative differences appeared. Qualitatively, a noticeable absence in the presence of cavities (or bubbles) was observed. In addition, an increase in fluorescing of the additive particles was noted. Figure 3 shows the CCD images of the different propellant mixtures. Quantitatively, the thoroughly mixed propellant on the far right of Fig. 3 demonstrated a greater degree of blue pixel intensity coupled with fewer variations in the intensity. An unexpected artifact of the fluorescing particle diagnostic was that the resulting fluorescence distribution so uniformly illuminates the samples that variations in the mixedness of the primary ingredients (namely the AP particles) can also be ascertained. The semitransparent nature of the AP crystals no doubt has something to do with the reflection,

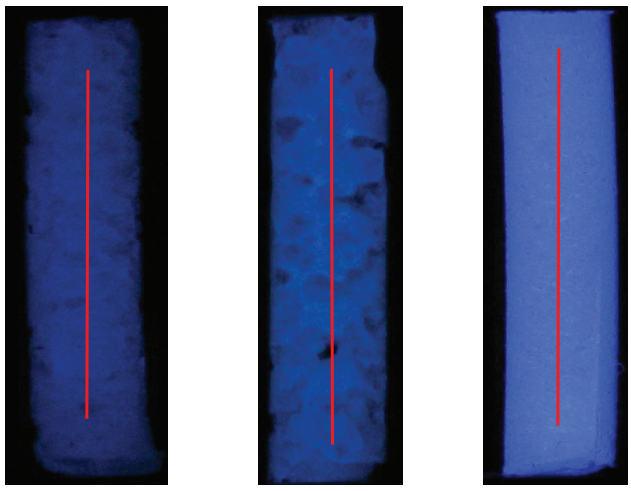


Fig. 3 Quantum dot-laced propellant strand samples with different degrees of mixedness. Lines drawn through the center correspond to the intensity plots seen in Fig. 4. Note that the fluorescing diagnostic gives not only an indication of the uniformity of the additive, but the features and mixedness of the primary ingredients are also elucidated.

transmission, and scattering of the emitted photons within the propellant. Further study on such phenomena is warranted.

The blue pixel intensity graphs comparing the three strands are provided in Fig. 4, which show light intensity versus position (i.e., pixel number) along the surface of the samples, near the middle. Note that the pixel numbers in Fig. 4 correspond to the lines drawn on each sample in Fig. 3. Most notable in Fig. 4 is that the well-mixed sample has about a factor-of-two greater intensity than the closest, less-mixed sample. Also noticeable is that there is little variation in intensity along the center line for the well-mixed sample, while the other two propellant mixtures show considerably more variation in intensity. This variation can also be seen with the naked eye in Fig. 3, evident by the regions of more and less fluorescence.

In a similar manner, Fig. 5 shows the CCD images of the propellant cross sections for the same three mixtures as in Fig. 3 and 6 depicts the blue pixel intensity graphs of the cross-section samples. The results are similar to those seen from the surface of the propellant (Figs. 3 and 4); that is, the well-mixed propellant is qualitatively (Fig. 5) and quantitatively (Fig. 6) more uniform and intense than the lesser-mixed propellant samples. Hence, continuity is seen within the data, whether the data were gathered on the surface of the propellant strands or from within the propellant cross sections.

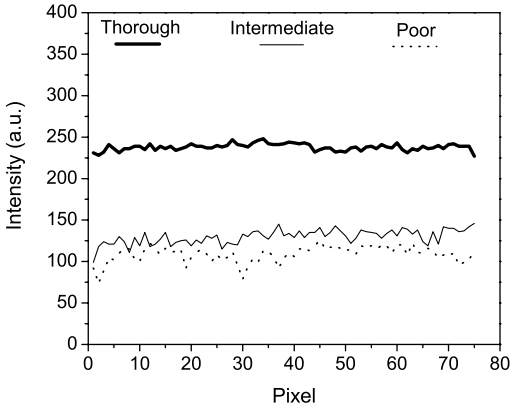


Fig. 4 Graphs of the blue pixel intensity of the quantum dot-laced propellant strands seen in Fig. 3.

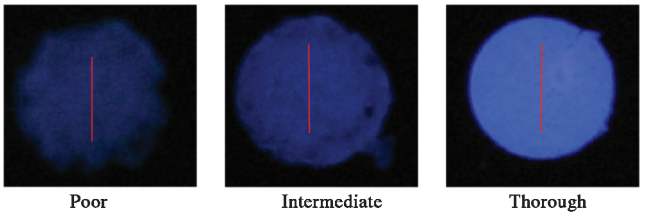


Fig. 5 Quantum dot-laced propellant cross sections with different degrees of mixedness. Lines drawn through the center correspond to the intensity plots seen in Fig. 6.

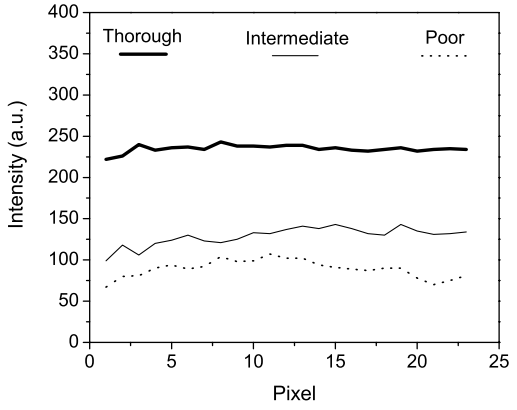


Fig. 6 Graphs of the blue pixel intensity of the quantum dot-laced propellant cross sections seen in Fig. 5.

B. Hand Versus Mechanical Mixing

Qualitative and quantitative inspection of hand and mechanically mixed fluorescing micron-laced propellants produced similar results. Qualitatively, there was an absence of noticeable cavities and cracks throughout both propellants. In addition, the surface integrity of each propellant was consistent. Digital images of the propellant strands are provided in Fig. 7. Quantitatively, the red pixel variation was very similar in each method. Figure 8 depicts the red pixel intensity comparison between the hand and mechanically mixed propellants. The results from both propellants are comparable in that they each have nearly identical fluorescence intensities, and they both show little variation in intensity over the length of the sample. The implication here is that both sets of propellant have nearly identical mixedness levels.

C. Trace Particle Distribution

Unexpectedly, even the trace-micron-additive propellant produced a highly fluorescing sample both qualitatively and quantitatively. Recall that this study involved the mixture in which only a sprinkling of a very small amount (<0.05%) of the fluorescing additive was introduced and allowed to mix into the propellant for only a short time. Qualitatively, the propellant lacked cavities and cracks as expected since the main constituents were fully mixed, but the entire propellant fluoresced more or less uniformly. However, on

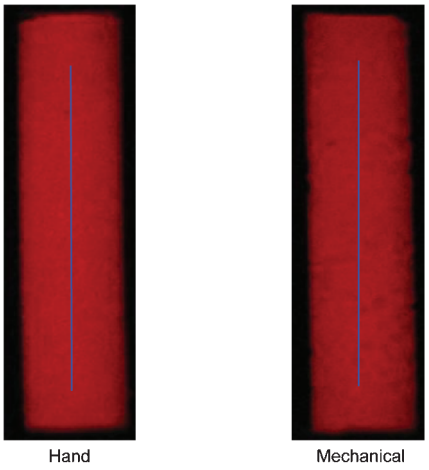


Fig. 7 Digital images of the hand and mechanically mixed propellants using the micron particles. Each image displays uniformity both in the fluorescing particles and in the primary ingredients. Lines drawn through the center correspond to the intensity plots seen in Fig. 8.

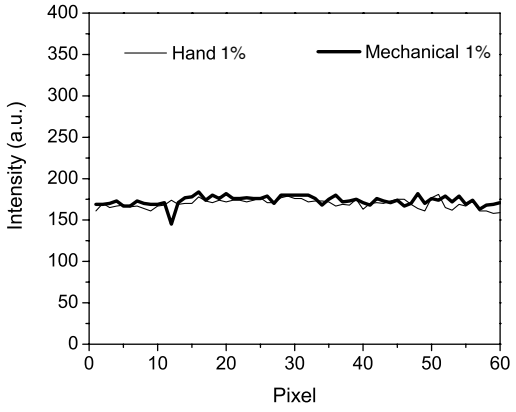


Fig. 8 Graphs of the red pixel intensity of the fluorescing micron-particle-laced propellant strands corresponding to the images seen in Fig. 7.

closer inspection there were small regions of extremely high fluorescence, indicating possible agglomeration of the sparse additive: the only indication of the intentionally sparse addition of the particles. Figure 9 contains a CCD image of the trace-fluorescing, hand-mix propellant strand. Quantitatively, the trace sample showed remarkably similar fluorescing intensity when compared with the 1% micron-laced, hand-mixed propellants (Fig. 7). Figure 10 graphically compares the trace strand propellant from Fig. 9 with the 1% hand-mixed propellant from Fig. 7.

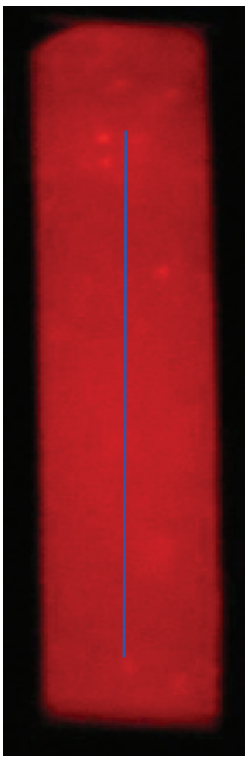
V. Discussion

In recent research, the authors have studied tailored solid composite propellants, mainly through incorporating burning rate-enhancing, nanosized additives. The purpose of the present study was to replace the burning rate additives with a similarly sized micron- and/or nanosized particles in a manner conducive to the mixing techniques in an effort to analyze the mixing process optically. Based upon the results, optical analysis of rocket propellants using fluorescing particles could be an effective tool both in assessing the distribution of the additives and in observing the mixedness of the primary ingredients. Some summary points are made as follows.

A direct correlation between the mixing time (i.e., mixedness) and both the fluorescing capabilities as well as the integrity of the propellant was noted. The poor and intermediate hand-mixed propellants fluoresced the least and were transparent in regions where only HTPB was present, whereas the thoroughly mixed propellant fluoresced the most and was opaque (Figs. 3 and 5). In addition, the poor and intermediate mixes had numerous cavities and cracks throughout the propellant, whereas the thoroughly mixed propellant did not. Collectively, it can be concluded that a propellant's mixedness is directly related to the optical characteristics of the propellant when doped with fluorescent particles, where an increase in fluorescing intensity coupled with a decrease in transparency correlates to a better-mixed propellant. This observation is further supported by the graphical data showing not only a higher degree of fluorescing intensity with improved mixing techniques, but fewer spatial variations in the intensity (Figs. 4 and 6).

The comparison of fluorescing-micron-additive hand and mechanically mixed propellants demonstrated the viability of both mixing techniques used in the authors' laboratory (Fig. 7). Each propellant shared similar qualitative and quantitative characteristics to the fluorescing nanoparticle sample that was thoroughly mixed. Qualitative inspection showed that each sample was opaque and lacked cavities and cracks. Quantitatively, their red pixel variations were very similar within the reproducibility of the samples prepared herein (Fig. 8).

This conclusion is further supported by empirical burning rate data for the same propellant formula used herein (i.e., 80%, 200-μm AP and 20% binder) that show the same measured burning rate from a mechanically mixed propellant when compared with a chemically identical, hand-mixed propellant. Figure 11 plots the burning rate data from the same period as the study of Stephens et al. [12], showing identical burning rate behavior between the hand and mechanically mixed propellants within the reproducibility of the burning rate data. Further details on the authors' strand burning procedure can be found elsewhere [3,4,14]. Therefore, it seems from the results herein that the fluorescing additive comparison showing identical intensity and uniformity between the two mixing methods (Figs. 7 and 8) correlate well with the overlapping burning rate results seen in Fig. 11. These early results show promise for using the additive tracer method as a way to compare propellant mixedness,



Trace

Fig. 9 Digital image of a propellant strand with a trace amount (less than 0.05% by mass) of fluorescing micron particles. Several regions of particle agglomerations are recognizable as the brighter spots of light. Line drawn through the center corresponds to the intensity plot seen in Fig. 10.

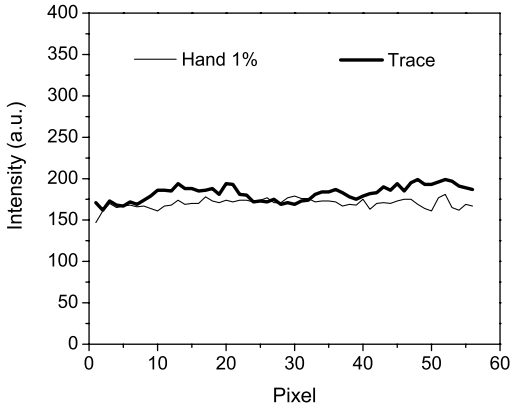


Fig. 10 Graphs of the red pixel intensity of thee fluorescing micron-particle-laced propellant strands comparing hand mixes with varying amounts of micron-fluorescing particles.

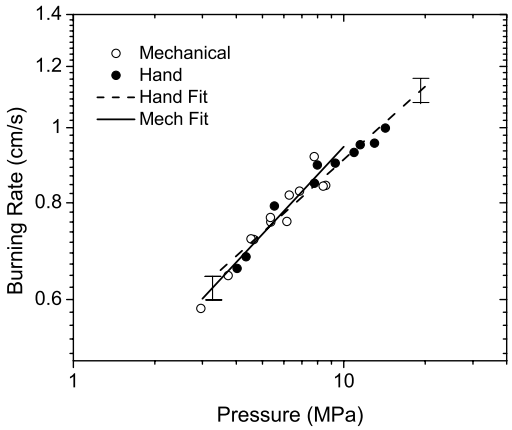


Fig. 11 Burning rate results for hand-mixed and mechanically mixed propellants having the same formula as the propellants in Figs. 7 and 8. The data were taken from the time period of the study of Stephens et al. [12] The burning rates between both methods agree favorably. Typical error bars are shown.

which may directly correspond to burning rate variations. Note, however, that burning rate comparisons between the well- and very poorly mixed propellant is not feasible for the batches herein since the voids in the poorly mixed sample would have resulted in extremely anomalous burning, namely runaway burning with unrealistically large burning rate exponents and even midburn explosions of the strand. Subtler changes in mixedness would be better for a future study to extend the comparisons between burning rate variations and fluorescing behavior.

Through comparison of a trace-micron-fluorescing sample with a 1% by mass hand-mixed propellant, the conclusion can be drawn that the mixing techniques used herein are effective. Even when extremely small amounts of fluorescing particles are added to a mix, the resulting propellant fluoresces throughout the sample (Fig. 9). The additives (both micron- and nanosized) seem to be very quickly dispersed within the propellant mixture. Another important note to this investigation is seen in the pockets of high intensity. The highly fluorescing areas suggest that the fluorescing micron particles may be agglomerating. Agglomerations appearing as bright dots of light could be used to help assess the relationship between mixing technique and the tendency of additive powders to agglomerate. Conversely, the lack of agglomeration spots in Figs. 3, 5, and 7 may indicate the absence of significant agglomeration of the nano- and micron-sized additives in those mixtures within the resolution of the camera and optical setup used in the present study.

While the original intent of present study was to use the quantum dot tracers as a substitute for catalytic nanoparticle additives to assess the quality of the mixing process involving nanoparticles, the success of the fluorescing particles as a mixing diagnostic can be used in other propellant-manufacturing and performance-assessing applications. For example, the uniformity of binder additives such as the curing agent can be assessed by first mixing the tracer with the curing agent and then introducing the tracer-laced agent in the usual fashion so that the tracers' locations would correspond to the presence of the curing agent as a function of time and position within the final propellant. In addition to burning rate, the mixedness of the propellant and its relation to mechanical properties can also be correlated with the fluorescence uniformity and intensity. With advances in nanotechnology and the ability to grow many variations of catalytic nanoparticles, future studies can be performed that investigate the use of additives that serve a dual purpose by both tailoring the burning rate (or mechanical properties) and assessing the mixedness of a propellant.

VI. Conclusions

Several solid composite propellant diagnostics are available for determining the mixedness of a propellant. However, most of these diagnostics focus on the presence of a specific species or the physical properties within a sample of a propellant but lack the ability to quickly characterize particle dispersion or mixedness within a propellant. In the present study, the authors effectively demonstrated a new optical diagnostic tool to aid in tailoring propellants, with emphasis on propellants containing nanosized additives. Experiments were conducted through the preparation of similar AP/HTPB-based composite propellants with a fluorescing-particle additive replacing a burning rate-enhancing additive to compare the validity of different mixing techniques as well as examining particle dispersion. The results showed similar patterns whether the fluorescing particle additive was a nanoparticle (quantum dot) or a micron-sized particle: the more thorough the mix, the greater the fluorescing capability of the sample. Whether comparing degrees of mixedness, mixing techniques, or assessing particle distribution, fluorescing particle analysis provides an additional cost- and time-effective technique for assuring quality control in propellant mixtures. In addition to verifying the authors' own mixing techniques, the results herein point towards future utilization of tracer additives to explore other solid propellant features related to curing agent uniformity and mechanical integrity, among others.

Acknowledgments

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