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Encapsulation of aluminum nanoparticles within copper oxide matrix for enhancing their reactive properties

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HIGHLIGHTS

- Al nanoparticles (NPs) are significantly oxidized by calcination process.
- CuO-encapsulated Al NPs are fabricated using a spray pyrolysis.
- CuO matrices protect Al NPs from thermal oxidation in the calcination process.
- The reactive properties of CuO-encapsulated Al NPs are much better than those of Al/CuO composites.

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ABSTRACT

Simple and easy spray pyrolysis and subsequent calcination processes were employed in this study to fabricate nanoenergetic materials (nEMs) composed of Al as the fuel and CuO as the oxidizer. Al nanoparticles (NPs) and $Cu(NO_3)_2$ as the CuO precursor were first dissolved in ethanol, and then they were pyrolized in the gas phase. After the subsequent calcination process, $Cu(NO_3)_2$ and its intermediate matrix covering Al NPs were completely transformed to the CuO matrix by thermal decomposition, and thus, the CuO-encapsulated Al NPs were successfully fabricated. The burn rate of the CuO-encapsulated Al NPs fabricated in this study was found to be much higher than that of Al/CuO composite NPs, which were fabricated for comparison by traditional sonication mixing and subsequent calcination processes. The ignition delay time and total burning time of CuO-encapsulated Al NPs were also much shorter than those of Al/CuO composite NPs. This suggests that the combination of spray pyrolysis and subsequent calcination processes can be a versatile and effective method to form the homogeneous and intimate nEMs composed of fuel materials (i.e., Al NP core) and oxidizers (i.e., CuO matrix) with high reactivity and excellent combustion properties.

1. Introduction

Energetic materials (EMs) possess chemical enthalpy, which can be rapidly turned into thermal energy when they are initiated by an external energy input. Generally, there are two types of EMs [1]: The first type, namely, the monomolecular EMs have the fuel and oxidizer within a molecule, e.g., nitrocellulose and nitroglycerine, which are generally produced by the combination of nitration [2–4], dehydration [5–8], and polymerization [9,10] processes. These EMs generate high power and exhibit a high energy release rate, which are strongly dependent on the chemical kinetics, the fuel and oxidizer balance, and the physical density of materials. The second type, i.e., the composite EMs are a mixture of fuel and oxidizer particles at the micro- and nanoscales. The composite EMs are produced by various physical mixing processes, such as milling [11–14], sonic wave-assisted physical mixing [15–21], sol-gel chemistry [22–24], electrostatic assembly [25], and molecular self-assembly [26]. The composite EMs generally exist in the form of powders. The energy release rate and combustion properties of composite EMs can be controlled by manipulating the rate of mass transfer between the reactants.

Various fabricating methods for composite nanoscale energetic materials (nEMs) have been developed because of their highly exothermic reactions compared to microscale energetic materials. In various nEM formulations, aluminum (Al) as a relatively stable

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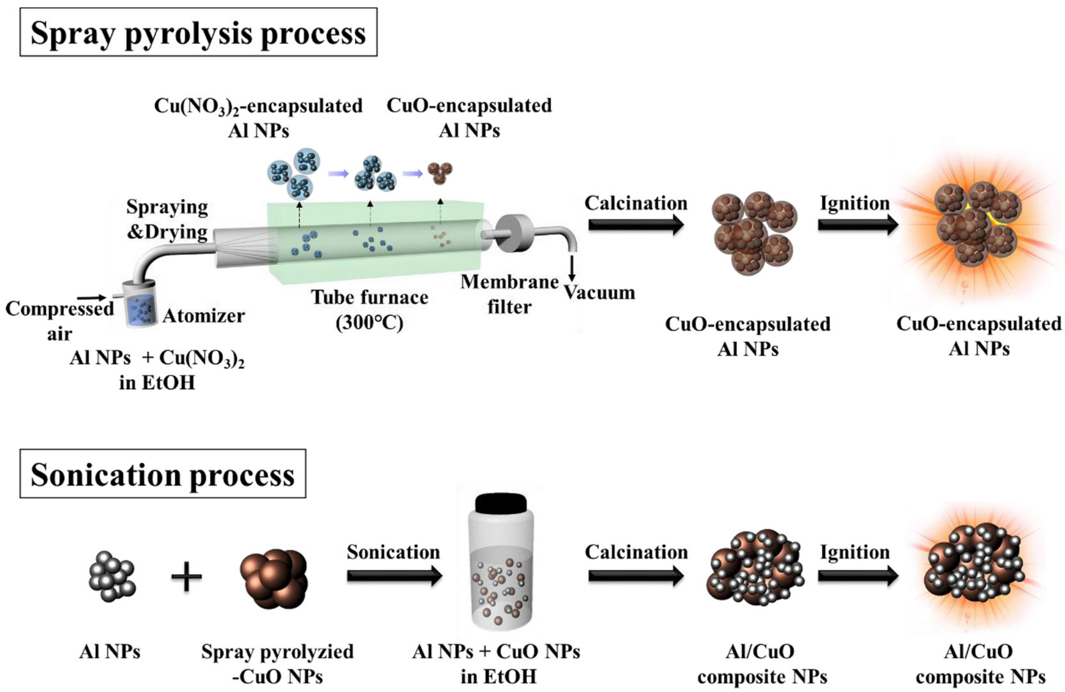

Fig. 1. Schematics of spray pyrolysis and sonication processes for fabricating CuO-encapsulated and Al/CuO composite nanoparticles (NPs), respectively, and their ignition and combustion properties after subsequent calcination process.

fuel metal is widely used in combination with various metal oxides [27–32]. Once the nEMs are ignited, a self-sustained exothermic reaction occurs within a fraction of a second. Therefore, the nEMs can be applied to thermal engineering, as explosives, propulsion fuels, and pyrotechnics for both civilian and military purposes [33–36]. In order to increase the energy release rate and combustion properties of nEMs, the degree of intermixing needs to be increased and the size of reactants should be decreased under the conditions of fixed chemical composition and mixing ratio of reactants. However, the aforementioned physical mixing methods experience inherent difficulties in fabricating uniformly intermixed nEMs neighboring at nanoscale distance [37]. Therefore, the encapsulation of fuel metal particles by metal oxidizers is a potential method to enhance the combustion properties of nEMs due to intimate contact between the fuel and oxidizer.

In this work, we demonstrate a versatile, simple and easy to scale-up method to fabricate nanoscale EMs (nEMs) using spray pyrolysis and subsequent calcination processes. With the use of the spray pyrolysis method, we can specifically employ metal (e.g., Al NPs) fuel seeds and metal nitrate (e.g., $Cu(NO_3)_2$) oxidizer precursor matrices, which are finally turned into a metal oxide (e.g., CuO) by subsequent calcination process. Thus, the CuO-encapsulated Al NPs are the final product fabricated in this study. We also have systematically investigated the effect of calcination conditions on the ignition and combustion properties of CuO-encapsulated Al NPs fabricated by the spray pyrolysis method. Further, the ignition and combustion properties of Al/CuO composite-based nEMs fabricated by the traditional sonication-based mixing and subsequent calcination processes are also examined for comparison.

2. Experimental details

Al NPs were commercially available from Nano Technology, Ltd. (Korea). They had an average size of approximately 80 nm and were used as the fuel metal without further treatment. In order

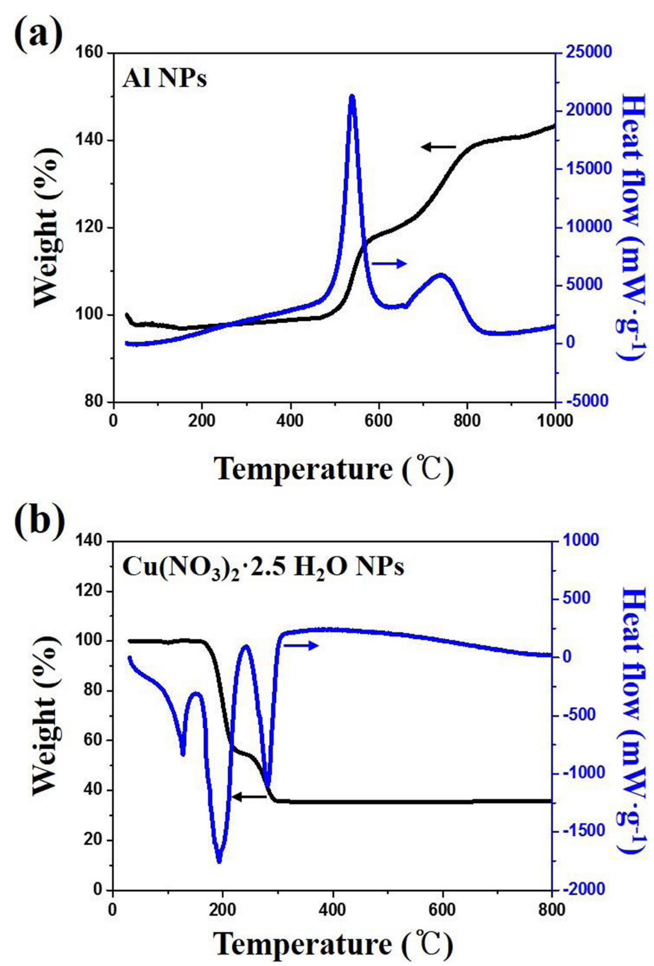

Fig. 2. Results of DSC and TGA analyses for (a) Al NPs and (b) $Cu(NO_3)_2{\cdot}2.5H_2O$ NPs.