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Tuning the ignition and combustion properties of nanoenergetic materials by incorporating with carbon black nanoparticles

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ABSTRACT

In this study, the effect of carbon black nanoparticle (CB NP) additives on the ignition and combustion properties of Al/CuO NP-based nanoscale energetic materials (nEMs) has been systematically investigated. When an excessive amount of CB NPs (>1 wt.%) was added to these nEMs, their pressurization and burn rates were considerably suppressed by a magnitude of about 50% due to the heat dissipation and thermochemical intervention in the self-propagating reactions of Al/CuO NPs. The ignition delay time of the studied energetic materials was monotonically reduced with increasing amount of added CB NPs because of the enhancement of their heat transfer properties. The total heat energy generated by the Al/CuO NP-based nEMs gradually decreased with increasing amount of CB NPs because of their thermochemical intervention in the exothermic reaction. Finally, the results of soil explosion testing revealed that the diameter of the produced crater could be controlled by varying the content of CB NPs in the nEM matrix. Therefore, the CB NP additives can be potentially used as a control medium, which affects the heat transfer process and thermochemical interactions between nEM components and is thus capable of precisely tuning their ignition, combustion, and explosion properties for various thermal engineering applications.

1. Introduction

Energetic materials (EMs) are composites containing fuel metal and oxidizer components, which are capable of storing chemical energy inherently and then rapidly converting it to thermal energy via external ignition [1–7]. Therefore, EMs are generally used in applications that require high energy conversion in a very short time such as explosives, pyrotechnics, and propellants. Recently, many research groups have investigated nanoscale EMs (nEMs) because their heat energy release rates are much larger than those of macro- and microscale EMs [8–10]. In addition, the thermal and combustion characteristics of nEMs (including thermal decomposition properties, sensitivity, and operational performance [11–15]) can be improved by controlling the size and homogeneous distribution of reacting components.

Controlling the ignition and combustion properties of nEMs is essential for various civil and military applications. Many research groups have attempted to achieve this by adding carbon materials into the nEM matrix. Bach et al. [16] developed insensitive nEMs by adding 5 wt.% of graphitized carbon black to Al/WO_3-based nEMs; as a result, the modified materials became significantly less sensitive to high magnitudes of mechanical impact and friction while exhibiting high electrostatic sensitivity due to the relatively small content of the carbon modifier. Kappagantula et al. [17] studied the influence of the Al/Teflon-based nEMs impregnated with various carbon nanomaterials (including multiwalled carbon nanotubes (MWCNTs), graphenes, and amorphous carbon nanospheres) on their ignition properties during mechanical impact. They found that the ignition energy of the fabricated nEMs decreased sharply at MWCNT contents below 1 wt.% and then increased slowly at higher MWCNT concentrations. On the other hand, when larger amounts of graphene and amorphous carbon nanospheres were added to the Al/Teflon-based nEMs, their ignition energy gradually decreased. However, it was difficult to quantify the ignition and combustion properties of nEMs by mechanical impaction because of the random formation of localized heating spots on the surface of the modified nEMs.

Carbon materials have been also utilized to improve the thermal properties of various functional composites because of their high thermal conductivity and good light absorption properties [18–24]. Among various carbon materials, carbon blacks (CBs) are frequently used as functional additives since they are relatively inexpensive and can be easily manufactured. Many research groups have used CBs as a light absorber for igniting nEMs by laser beam irradiation [16,23,24]. However, the role of CBs as a heat transfer medium in the nEM matrix ignited by various thermal heat sources

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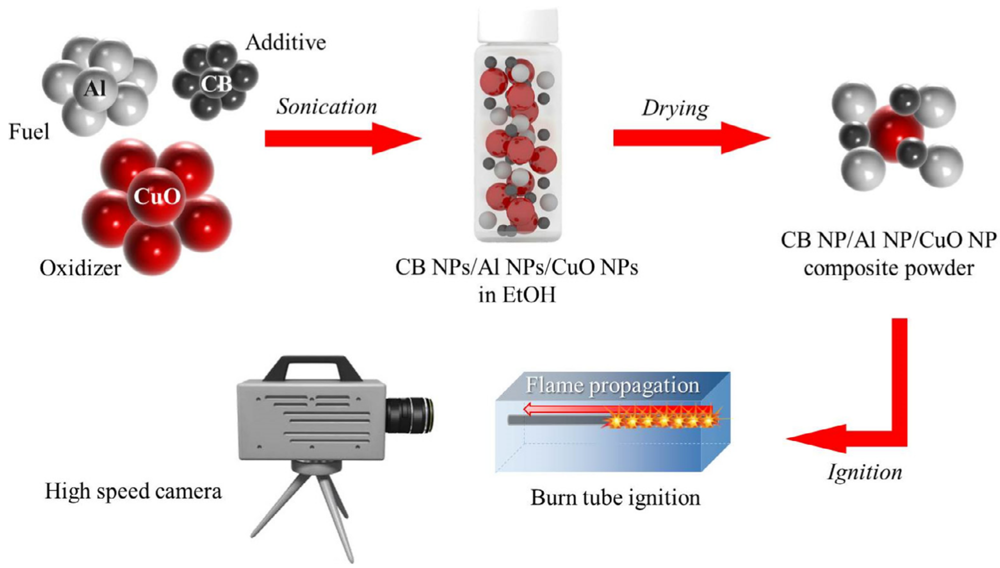

Fig. 1. A schematic describing the fabrication of CB/Al/CuO NP composite powders and testing their combustion properties using a cylindrical burn tube.

has not been systematically explored yet. Generally, nEMs containing Al particles as the fuel metal have relatively low thermal conductivity due to the existence of an oxide layer on their surface [25]. In order to enhance the heat transfer properties of Al-based nEMs, the addition of CBs to their matrix can be considered as a potential strategy. Therefore, it is very important to examine the ignition and combustion properties of the CB-modified Al-based nEMs as a potential heat transfer medium. In this work, we systematically investigated the effects of the addition of CB nanoparticles (NPs) on the ignition and combustion properties of Al/CuO NP-based nEMs (here Al NPs, CuO NPs, and CB NPs were used as the fuel metal, oxidizer, and heat transfer medium, respectively).

2. Experimental

2.1. Fabrication of CB/Al/CuO composites

In this study, Al, CuO, and CB NPs were mixed to fabricate CB/Al/CuO NP-based composite powders and pellets. Commercially available Al (NT base Inc., Korea), CuO (NT base Inc., Korea), and CB (Ketjenblack EC-300 J, Akzo Nobel Functional Chemicals, USA) NPs with average particle sizes of 78 ± 2.3 nm, 130 ± 5.3 nm, and 47 ± 1.3 nm, respectively, were used without further modification. The fabricated CB/Al/CuO NP composites were ignited using a cylindrical burn tube to examine their ignition and combustion properties (Fig. 1).

To fabricate the Al/CuO-based nEM composites, Al NPs were mixed with CuO NPs in ethanol (EtOH) solution at an Al:CuO mixing ratio of 30:70 wt.%, which corresponded to the optimum combustion conditions [26–28]. After that, various amounts of CB NPs (0.0, 0.1, 0.3, 0.5, 1, 3, 5, and 10 wt.%) were added to the nEM-containing dispersion. To achieve a homogeneous dispersion of CB, Al, and CuO NPs in EtOH, it was sonicated for 30 min at a power of 200 W and frequency of 40 kHz. After drying the CB/Al/CuO NP-dispersed solution for 15 min inside a convection oven heated to 80 °C, the obtained CB/Al/CuO NP composite powders were characterized using a field emission scanning electron microscope (FE-SEM; Hitachi, Model S-4700) operated at a voltage of 15 kV and transmission electron microscope (TEM; FEI, Model Talos F200X) operated at a voltage of 200 kV. In addition, to examine ignition and combustion properties of CB/Al/CuO NP composite powders, a series of burn tube tests were conducted (see Fig. 1). Briefly, ~200 mg of the CB/Al/CuO NP composite powders were filled with in a polyethylene terephthalate (PETE) tube with a 3 mm in diameter and 50 mm in length, and then PETE tubes were inserted into a transparent acrylic block. The one end of burn tube was ignited using a hot-wire, and then the flame propagation toward the other end was recorded using a high-speed camera.

2.2. Characterization of ignition and combustion properties of CB/Al/CuO NP composites

To examine the ignition and combustion properties of the fabricated CB/Al/CuO NP composite powders and pellets, various characterization methods including pressure cell testing (PCT), temperature jump (T-jump) ignition testing, high-speed camera analysis, and thermogravimetric and differential scanning calorimetry (TG-DSC) were utilized. A PCT procedure was used to analyze the pressure traces and pressurization rates of the composite powders after their ignition inside a 13-mL sealed pressure cell [30]. It was conducted by placing 16 mg of the tested powder in the sealed pressure cell and igniting it with a hot tungsten wire at a current of 2 A and voltage of 1.5 V. The pressurization rate was calculated by measuring the maximum pressure and corresponding rise time after the tested powders were detonated. A high-speed camera (Photron, Model FASTCAM SA3 120 K, 30,000 FPS) was utilized to measure the burn rate and total burning time of the composite powder. To determine the ignition delay times of the fabricated CB/Al/CuO NP composites, they were subjected to a T-jump testing procedure [29–33]. Pt wire with a diameter of 10 μm was coated with the prepared CB/Al/CuO NP powder by mixing 20 mg of the tested composite with 200 mg of the EtOH:H_2O solution with a mixing ratio of 44:56 wt.% [34] followed by the sonication for 30 min at a power of 200 W and frequency of 40 kHz. To measure the heat flow generated by various CB/Al/CuO NP composites, TG-DSC (Setaram, Model LABSYS evo) analysis was performed in a nitrogen gas environment and the temperature range from 30 °C to 1000 °C at a heating rate of 10 °C min^{-1}.

3. Results and discussion

According to the results of FE-SEM analysis, the fabricated CB/Al/CuO NP composite powders had spherical shapes and were highly aggregated (the average diameters of Al, CuO, and CB NPs