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Electrophoretic assembly of B–Ti nanoenergetic coating for micro-ignitor application

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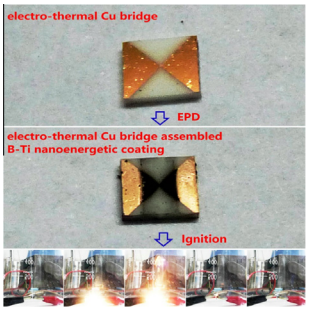
HIGHLIGHTS

- B–Ti nanoenergetic coating was assembled via electrophoretic deposition.
- Combustion test indicates quick energy releasing happened to B–Ti coating.
- Ignition of Cu bridge assembled with B–Ti coating is exciting for ignitor application.

GRAPHICAL ABSTRACT

Micro-ignitor assembled with electrophoretic B–Ti nanoenergetic coating can be successfully ignited with huge energy output.



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ABSTRACT

B–Ti nanoenergetic coating has received great attention on its high theoretical heat of reaction up to 5525 J g^{-1}, which have great potential in enhancing the energy output of various function devices, including the micro-igniter device. In this work, B–Ti nanoenergetic coating was successfully fabricated via electrophoretic co-assembling of boron nanoparticles and titanium nanoparticles in a mixed solvent of ethanol–acetylacetone (1:1 in volume) containing 0.2 mM nitric acid. When electrophoretic deposition (EPD) were performed at higher concentration of B and Ti nanoparticles, more nitric acid is needed for sufficient surface charging. DSC curves show that the values of heat release in electrophoretic B–Ti nanoenergetic coating is 3329 J g^{-1}. A violent and quick energy releasing of the B–Ti coating is successfully confirmed by the combustion test. With a significant enhancement in energy output by the electrophoretic B–Ti nanoenergetic coating, electro-thermal Cu bridge can be successfully ignited, exhibiting an exciting improvement in micro-ignitor application.

1. Introduction

In recent years, nanoenergetic materials based on metastable intermolecular composites have been widely studied for their superior features including high energy density, high burning rate, high heat production [1–8]. Especially, intermetallic compounds, such as B–Ti alloy, is widely regarded as a type of promising

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reactive material with high theoretical heat of reaction up to 5525 J g^{-1} [9], (Table 1), which have many potential device applications.

The micro-ignitor device is one of these important applications in the fields of micro-electro-mechanical system (MEMS) technologies, in which these energetic materials could be applied as coatings to improve the ignition process. Many efforts have been devoted onto fabricate energetic materials as coatings for the purpose of enhancing energy output [10–15]. To improve the quality of the coatings and its energy output, a class of novel technologies have been developed, such as thermal evaporation [13,16–18], magnetron sputtering [14,19–21], cold spray [22], electron-beam evaporation [15], electrospuning [23] and electrophoretic deposition (EPD) [24–30]. Comparing with other methods, such as sputtering, EPD method has exhibited great potential in fast and economical assembling of nanoparticles into corresponding energetic coatings, taking advantages of simplicity, low cost, easy control of the film thickness, wide adoptability for complex shapes, and fast fabrication process (μm min^{-1} for EPD *vs* nm min^{-1} for sputtering).

In this work, we introduced a novel dispersion mixture containing both nano boron particles and nano titanium particles, which enabled a successful fabrication of energetic B–Ti nanocomposite (B–Ti) coating via EPD method. The thermodynamic properties and combustion performance of the energetic B–Ti coating were also studied. Furthermore, the B–Ti nanoenergetic coating was assembled on electro-thermal bridge for practical MEMS devices application, while its related ignition behavior was also investigated.

2. Experimental section

2.1. EPD of B–Ti nanoenergetic coating

Nano titanium (nano Ti, 40 nm, 99.9%), Nano boron (nano B, 100 nm, 99.9%) were bought from Beijing DK Nano Technology Co., ltd (Beijing, China) and directly used without purification in the study.

In energetic reactions, the equivalence ratio was defined as the actual boron to titanium ratio divided by the boron to titanium ratio in a stoichiometric reaction:

$$\Phi = \frac{(B/Ti)_{actual}}{(B/Ti)_{stoich}} \quad (2.1)$$

The stoichiometric boron: titanium ratio was 2:1 from the balanced reaction:

$$2B + Ti \rightarrow TiB_2 \quad (2.2)$$

In order to explore the desirable dispersion system, the EPD of nano B and EPD of nano Ti were separately performed using solutions of the same concentration before co-deposition of nano B and nano Ti. Ethanol–acetylacetone (1:1 in volume) was employed as the solvent for the suspension mixture, and nitric acid was added as additive. For all EPD processes, the solid loading amount was 1 g L^{-1} unless otherwise stated. For the co-deposition process, the equivalence ratio of nano B to nano Ti in suspension (Φ_s) was adjusted in weighting samples. The suspensions were dispersed under ultrasonic for 30 min to break up agglomeration. Before applied in EPD, stainless steel substrates with dimensions of 0.1 × 40 × 85 mm^3 were cleaned in ethanol for 20 min.

Table 1
The theoretical heat of reaction of different kinds of intermetallic reactive materials [9].

Reactant	ΔH (cal g^{-1})	Reactant	ΔH (cal g^{-1})
B–Ti	1320	Si-Ti	428
Al-B	742	B-V	536
Si-V	700	Al-Ni	330
B-V	650	Al-Ti	314

The EPD was performed in a beaker with two electrodes vertically immersed in a suspension of 200 mL with a constant voltage of 100 V. Stainless steel sheets with a deposition area of 55 × 40 mm^2 were used as both anode and cathode. The distance between the anodic and cathodic electrodes was fixed as 10 mm. After deposition, the cathode was removed from the suspension. The as-deposited films were dried in the oven at 80 °C for 1 h, and the deposit was weighted by an electric balance with accuracy of 0.0001 g.

2.2. Characterization

The phase composition of the coatings was measured with X-ray diffraction (XRD, 6000, Shimadzu, Japan). The morphology and element distribution of the coating were analyzed using a field emission scanning electronic microscope (FESEM, JSM-7800F, JEOL) and energy dispersive spectroscopy (EDS).

Due to the insolubility of Ti nanoparticles in acid media, the equivalence ratio in deposited B–Ti coating (Φ_s) was measured by the following precipitation weighing method: after dissolving nano-B in deposited B–Ti coating s with 5 M nitric acid, the unsoluble Ti nanoparticles was dried and weighted, and the equivalence ratio in deposited coating (Φ_s) was calculated.

2.3. Thermodynamic properties and combustion performance study

The exothermic reactions of B–Ti nanoenergetic coatings were investigated by differential scanning calorimetry (DSC, STA449F3, NETZSCH, Germany). The DSC experiments were carried out at a temperature range from 100 to 1000 °C at a heating rate of 10 K min^{-1} under a 99.999% Ar flow.

In order to analyze the combustion performance, custom-made resistance wires (Cr20Ni80, 5.551 Ω m^{-1}) with diameter of 0.5 mm and length of 40 mm were used for preparing B–Ti nanoenergetic coating samples. The fabrication process and ignition experiment were performed according to the reported method [31].

Movies of the combusting material were taken with a high-speed camera (HG-100K, Redlake, USA) at an imaging speed of 10,000 frames per second. The data collection was post-triggered digitally after the reaction was observed.

2.4. Ignition test of electro-thermal Cu bridge assembled with electrophoretic B–Ti nanoenergetic coating

To explore the feasibility of B–Ti nanoenergetic coating in MEMS devices, the custom-made electro-thermal Cu bridges were used as cathode and then B–Ti nanoenergetic coating were assembled on them via EPD. These electro-thermal Cu bridges with electrophoretic B–Ti nanoenergetic coating were ignited by a constant current of 0.9 A supplied by direct current power.

3. Results and discussion

3.1. EPD for both nano-B and nano-Ti

It is well known that successful EPD mainly depended on a suitable dispersion media to make specific kind of particle charged and move directionally under electric-field [32,33]. Therefore, a suitable dispersion media was the key issue for successful EPD. For EPD of different kinds of particles, the dispersion mixture needed to be optimized case by case, in order to provide a suitable