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Assembly and reaction characterization of a novel thermite consisting aluminum nanoparticles and CuO nanowires

Yi-Chun Chiang [a], Ming-Hsun Wu [a,b,*]

[a] Department of Mechanical Engineering, National Cheng Kung University, Tainan 70101, Taiwan
[b] Research Center for Energy Technology and Strategy, National Cheng Kung University, Tainan 70101, Taiwan

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Abstract

A novel approach for assembling Al/CuO thermite consists of aluminum nanoparticles and cupric oxide nanowires has been successfully developed in this study. Aluminum nanoparticles were driven into gaps in the cupric oxide nanowires layer on a copper wire through electrophoretic deposition in this method. The cupric oxide nanowires along with oxide layers were grown on the copper wire via thermal oxidation, and the remaining copper core was the negative electrode that attracted aluminum particles carrying positive surface charges in the ethanol/water solution during electrophoretic deposition. A nanothermite shell enclosing the copper wire was obtained after the process. Considerable heat release from the thermite wire was observed starting from ~400 °C in differential scanning calorimetry measurements. Exothermic solid–solid thermite reactions were fully ignited at 529 °C, and the heat release peaked at 566 °C. Above the melting temperature of aluminum, another heat release peak, which could be associated with reactions between liquid aluminum and the remaining oxides, was detected at 760 °C. Overall heat release of the nanothermite wire assembled with 80 V and 10 s electrophoretic deposition was 3108 J/g. Reaction propagation speed along the nanothermite wire with 10 s electrophoretic deposition was the highest at 43.8 cm/s, and longer deposition durations resulted in slower burning speeds.

Keywords: Nanothermite assembly; Electrophoretic deposition; Al/CuO nanothermite; Copper oxide nanowire

1. Introduction

Nanothermites contain nano-sized particles of metal and metal oxides, and are able to release large amount of energy in a very short duration when ignited. This type of energetic material is also called metastable intermolecular composites (MIC). By bringing a high reactivity metal and a passive metal oxide together at nanoscale, the ignition

* Corresponding author at: Department of Mechanical Engineering, National Cheng Kung University, 1, University Rd, Tainan 70101, Taiwan. Fax: +886 6 2352973.
E-mail address: minghwu@mail.ncku.edu.tw (M.-H. Wu).

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temperature is reduced and the burning velocity is enhanced due to the much higher interfacial contact area and shorter diffusion length between fuel and oxidizer [1]. Even more interestingly, heat release is usually accompanied with the large amount of gas generation in many nanothermite reactions. These unique combustion features of nanothermites have opened up new applications in propellant, welding, explosives, pyrotechnics, biocidal, and drug delivery [2–7].

Packing density, homogeneity of the composite material as well as sizes and geometries of the constituents are all able to influence combustion performance of nanothermite. But manipulability of these parameters are sometimes limited by the assembly method applied. Nanothermites are typically prepared by physical mixing of metal and metal oxide particles that nanothermite powders are obtained. The method begins with dispersing nanoscale fuel and oxidizer particles in an organic solution through ultrasonication, and then vaporize the dispersion medium to obtained dry thermite powders [8]. However, nanothermites usually have to be packed into confinements or deposited at specific locations in applications. Handling of these highly sensitive thermite powders by itself is a difficult task, not to say the integration of the powder form thermite into microsystem such as microthrusters and microactuators. Controlling the homogeneity and packing density of thermite powder in the integration process is another challenge. Therefore, various other approaches, including arrested reactive milling [9], sol–gel [10], self-assembly [11,12], chemical vapor deposition [13–15], electrophoretic deposition (EPD) [16,17], electrospray [18], biosynthetic [19], and DNA strands complement [20], were developed to address these issues and challenges.

Electrophoretic deposition has been used to deposit nanoscale thermite powders on a platinum wire patterned on a silicon wafer [16,17]. Superior homogeneity was found in the EPD deposited samples, and better reproducibility of the nanothermite was achieved comparing to drop casted approach. But aluminum micro- or nano- particles and CuO nanoparticles were still mixed in ethanol/water solution via ultrasonication like the physical mixing approach. Stratification of the thermite layer may exist due to the difference between the zeta potentials of CuO and Al particles, which were both dispersed in the colloid during EPD.

Chemical vapor deposition is another promising nanothermite assembly method that is inherently compatible with microfabrication process. Nanowired Al/CuO thermites have being successfully fabricated using this method, in which CuO nanoparticles in powder-based Al/CuO nanothermites are replaced with CuO nanowires (CuO NW) grown on the copper film. The assembly begins with depositing a layer of copper on a silicon wafer via either thermal evaporation or electroplating. Thermal oxidation is then utilized to grow cupric oxide nanowire array on the copper layer. The nanowired Al/CuO thermite was finalized by evaporating a layer of aluminum on the CuO NW. The contact area between Al and CuO are largely enhanced due to the very large surface area of CuO NW array comparing to a planar CuO layer. With the intimately bonded core-shell or layered structure, the diffusion distance between fuel and oxidizer is minimized, and the theoretical maximum density is nearly 100%. Exothermic reactions were observed at temperatures below the melting temperature of aluminum through DTA measurements. Chemical vapor deposition has also been utilized to fabricated layered nanothermite by alternately depositing Al and CuO layers

This paper reports a novel method to assembly nanothermite comprised of aluminum nanoparticles (Al NP) and CuO NW on a copper wire, and the reaction characteristics of the nanothermite. CuO NW was directly grown on a copper wire through thermal oxidation. Instead of plating an aluminum layer on CuO NW via chemical vapor deposition, Al NP were inserted into the gaps of the copper oxide nanowire cluster through electrophoretic deposition. Only Al NP had to be dispersed in the dispersion medium since the oxidizer, CuO NW, was already on the copper wire. A thin thermite layer was obtained on the surface of the copper wire after the process. Reaction properties of the assembled thermite wire were quantitatively characterized. Ignition temperatures and heating values of the nanothermite wires were determined using differential scanning calorimetry (DSC). Burn tests were also performed to obtain linear burning rates of the nanothermite shells on copper wires.

2. The assembly concept and process

The concept of assembling nanothermite via electrophoretic deposition of aluminum nanoparticles into cupric oxide nanowire array was schematically shown in Fig. 1. The aluminum nanoparticles carry positive surface charges in ethanol water solution. By taking the copper wire covered with cupric oxide nanowire as the negative electrode, aluminum nanoparticles are driven into the nanowire array to form the binary energetic composite when an electric field is applied across the solution. Reaction characteristics of the nanothermite can be tuned through manipulating process parameters including CuO NW number density and geometry, size of Al NP as well as EPD duration and electric field strength in this approach. Handling problems associated with nanothermite powders are largely avoided since the thermite layer is directly formed on a copper wire. Scalability is