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Copper-polydopamine composite derived from bioinspired polymer coating

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ABSTRACT

Metal matrix composites with nanocarbon phases, such carbon nanotube (CNT) and graphene, have shown potentials to achieve improved mechanical, thermal, and electrical properties. However, incorporation of these nanocarbons into the metal matrix usually involves complicated processes. This study explored a new processing method to fabricate copper (Cu) matrix composite by coating Cu powder particles with nanometer-thick polydopamine (PDA) thin films and sintering of the powder compacts. For sintering temperatures between 300 °C and 750 °C, the Cu-PDA composite samples showed higher electrical conductivity and thermal conductivity than the uncoated Cu samples, which is likely related to the higher mass densities of the composite samples. After being sintered at 950 °C, the thermal conductivity of the Cu-PDA sample was approximately 12% higher than the Cu sample, while the electrical conductivity did not show significant difference. On the other hand, Knoop micro-hardness values were comparable between the Cu-PDA and Cu samples sintered at the same temperatures.

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1. Introduction

Nanocarbons, such as carbon nanotube (CNT), graphene, and reduced graphene oxides (rGO), exhibit superior mechanical, thermal, and electrical properties [1–3]; and various studies have demonstrated that incorporation of nanocarbons into metal matrices can lead to improved properties including mechanical strength [4,5] and thermal conductivity [6–8]. For example, Kim and coworkers [5] found that the nanopillar compression strength of copper was improved by two orders of magnitudes when single-layer graphene was introduced in matrix. Goli et al. [7] observed an increase of up to 24% in the thermal conductivity of graphene-Cu-graphene heterogeneous films where few-layer graphene was deposited on both side of Cu. Thermal conductivity of a composite is highly dependent on the microstructure and distribution of each phase. In some cases thermal conductivity could be impeded by phonon scattering due to addition of interfaces; and in other cases the favourable orientation and formation of network of the second phase could enhance thermal conductivity [9]. Subramaniam et al. [10] reported that high-temperature electrical conductance of copper could be enhanced by inclusion of CNTs aligned in the electric current direction.

Metal-nanocarbon composite materials can be manufactured using various physical or chemical methods. For example, they may be fabricated by mechanical mixing of metal and nanocarbon powders with or without aid of liquids, followed by various consolidation methods [11–13]. The composites may also be obtained by blending nanocarbon powders into metal melts [14,15]. However, it is often difficult to achieve good distribution of the nanocarbon phase through these physical blending methods. On the other hand, composite powders may be fabricated by either growing nanocarbons on metals [16,17] or growth of metal particles on the nanocarbon phase [10,18]. However, material manufacturing beyond the laboratory scale still present a challenge for these approaches [10,16–18].

In this study, we explored a new processing method to fabricate Cu-nanocarbon composite using polydopamine (PDA) as the carbon source. PDA is considered as a biopolymer synthesized through oxidation/polymerization of dopamine (DA) molecules [19]. Multiple functional groups, including amine (-NH_2) and hydroxyl (-OH) groups, contribute to the affinity of PDA to many material surfaces [20,21], making PDA a “universal” adhesive/surface modification agent [22]. Furthermore, PDA was shown to possess reductive property that can facilitate reduction of metal ions [23].

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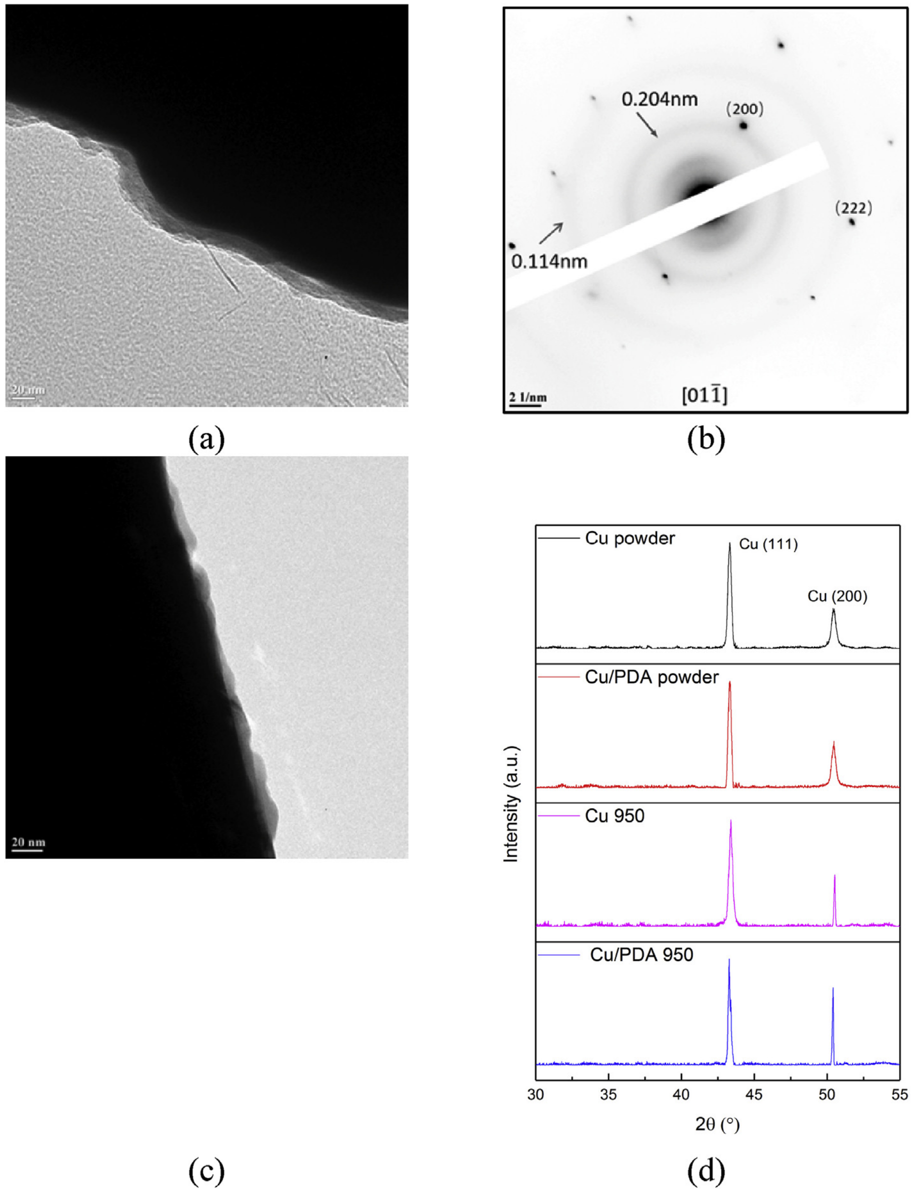

Fig. 1. (a) TEM image showing the PDA coating on a Cu particle prior to compaction and sintering. (b) Selected area electron diffraction (SAED) obtained from PDA-coated Cu powder sample. (c) TEM image of a PDA-coated Cu particle after heat treatment at 500 °C. (d) X-ray diffraction profiles of uncoated and PDA-coated Cu powders before and after thermally annealed at 950 °C.

Thermal annealing of PDA under inert or reducing atmospheres can result in carbon-like materials with high electrical conductivities, which were termed as carbonized PDA (cPDA) [24] or pyrolyzed PDA (pPDA) [25]. For example, Li and coworkers [25] found the electrical conductivity of cPDA reached 1.2×10^5 S/m after heat treatment at 1000 °C. Kong et al. also reported electrical conductivities as high as 2.6×10^5 S/m for cPDA films [24]. The high electrical conductivity of cPDA was likely a result of its graphite-like structure. Ai and coworkers [26] proposed a hypothetical structure of cPDA, which is essentially nitrogen-doped graphene, where nitrogen atoms exist either in the graphitic state or the pyridinic state. The conversion process from amorphous PDA to nanocrystalline graphitic cPDA was discussed in our recent study [27].

In this study, copper powder particles were coated with PDA thin films followed by uniaxial compression and sintering. It was observed that the sintering behavior of the composite powder was enhanced, which resulted in improvement in thermal conductivity for all sintering temperatures and electrical conductivity when the sintering temperature ranged between 300 °C and 750 °C. On the other hand, Knoop micro hardness was not affected by the introduction of PDA in the composites.

2. Materials and methods

Copper powder (14–25 μm, 99%) and dopamine (DA) chloride were purchased from a commercial source (Sigma Aldrich, St. Louis, MO, USA) and used without further treatment. In a typical coating experiment, 0.124 g of dopamine chloride was completely dissolved in 50 mL of 50 mM Tris buffer (pH = 8.5, ThermoFisher Scientific Inc., Waltham, MA). After adding 10 g of Cu powders to the dopamine Tris solution, the suspension was agitated in air using a magnetic stirring bar for 1 h. Tris buffer and PDA particles were removed by repeated (three times) centrifugation and dilution with deionized water. The Cu powder was collected through filtration

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