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Enhanced strength and excellent transport properties of a superaligned carbon nanotubes reinforced copper matrix laminar composite

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ABSTRACT

Superaligned carbon nanotube (SACNT) reinforced copper matrix laminar composites have been fabricated by means of the traditional copper sulfate electroplating process. The mechanical properties and transport properties of the Cu/SACNT composites with different SACNT content have been studied systematically, and the experimental results show that the as-prepared composites possess a better comprehensive performance than pure copper. The simple rule of mixtures (ROM) has been used to estimate the potential maximum properties of the Cu/SACNT composites. The Cu/SACNT composite is considered to be a promising material for electronics and communications applications.

1. Introduction

Copper is one of the most important functional materials and plays an indispensable role during the process of human development. It has been widely used in the fields of electrics, electronics and communications, etc. With the rapid development of science and technology, all kinds of applications in reality require higher and higher performance on copper. A large number of researches have made attempts to obtain high strength and high conductivity in copper materials [1–4]. However, it seems that high strength and high conductivity are mutually exclusive properties, because the common mechanism for high strength is to introduce a lot of defects to block the dislocation motion, whereas the conductivity usually decreases as a result of the scattering of electrons by defects. By using particular crafts, some progress have been made in improving the mechanical and electrical properties [5,6], however, their small size and complex processes are obstacles to their application in practice.

In the actual application, not only the strength and electrical conductivity but also a series of other properties such as thermal conductivity, corrosion resistance and high temperature performance should be considered. Most of the preparation methods are impossible to balance so much properties. To give the copper an excellent comprehensive properties, "composite method", which can reserve the properties of every component and add novel properties to the integral material, has received a great deal of attention.

There are a number of researches about copper matrix composites with various reinforcements, among which the carbon nanotubes (CNTs) first reported by Iijima in 1991 [7] have held a much higher appeal due to their unique atomic structure and fascinating mechanical, electrical, and thermal properties [8–12]. Researchers have used CNTs to improve the properties of copper, including mechanical strength [13], electrical conductivity [14], current density [15], thermal conductivity [16], and high temperature thermal stability [17]. However only one or two properties are involved in the existed researches. In addition, due to the small size of an individual carbon nanotube, electrons propagate only along the tube's axis. Compared with non-aligned CNTs, high orientation of the CNT along with the conducting direction is more helpful to achieve an excellent electrical property. But in the most of ever prepared bulk Cu/CNT composites, the CNTs are always dispersed randomly and discontinuously, resulting in the unsatisfactory experimental data about electrical properties.

Superaligned CNT (SACNT) film [18] is a continuous CNT film with highly oriented structure, in which the axes of CNTs are all lined up in one direction and the continuous film has both the excellent properties of nanometer sized CNTs and macrostructure like carbon fibers. Up to now, the SACNT has been used to prepare CNT/polyvinyl alcohol (PVA) composite yarns [19] and CNT/epoxy composites [20,21]. And to our best knowledge, it is the first time that our group has initiated a research topic about SACNT reinforced copper matrix composites [22].

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This study presents the enhanced strength and excellent transport properties of SACNT reinforced copper matrix composites processed by electroplating. Compared to the Cu/CNT composites prepared by other methods, our process has such many advantages as easy control of the distribution and continuous structure of the SACNT in the composites, large size and large scale production abilities.

2. Experimental

2.1. Preparation of Cu/SACNT composites

Superaligned multi-walled CNT arrays on a silicon wafer were provided by Tsinghua-Foxconn Nanotechnology Research Center. When pulling the CNTs from the superaligned arrays, a continuous and aligned CNT film could be formed by the action of the Van der Waals force which makes the CNTs join end to end [23]. Electroplating was performed in an electrolyte of $CuSO_4{\cdot}5H_2O$ (300 g/L), H_2SO_4 (50 g/L), and glucose (10 g/L) at room temperature. The preparation procedure is depicted schematically in Fig. 1, and a detailed procedure of sample preparation is reported elsewhere [22].

Four different volume fractions of SACNT film (0.26%, 0.52%, 0.78% and 1.04%) and a sample without SACNT film (0%) under the same experimental conditions were prepared. The volume fraction of the SACNT film in the composite are calculated by

$$V_s = \frac{m_s \rho_c}{m_s \rho_c + (m - m_s)\rho_s} \tag{1}$$

$$m_s = anS \tag{2}$$

where V_s stands for the volume fraction of the SACNT film, m_s signifies the mass of the SACNT film in the sample of composite, m is the mass of the sample of composite, ρ_c (8.96 g/cm^3) is the density of copper, ρ_s (1.8 g/cm^3) is the density of multi-walled carbon nanotubes in the SACNT film, a (1.5 μg/cm^2 [24]) denotes the typical mass per unit area of the SACNT film, n (20, 40, 45, 60) stands for the total number of SACNT film layers, and S is the area of the sample.

2.2. Performance measurement and structure characterization

The as prepared composites, with thickness between 60 μm and 80 μm, were cut into specific sizes for performance test.

Mechanical testing was accomplished in an Instron5848 tensile tester, and each specimen was about 70 mm long and 5 mm wide. The crosshead speed and the gauge length were 0.5 mm/min and 30 mm, respectively. In order to take repeatability into account, the test results for mechanical strength were obtained from the average of five readings.

The electrical conductivity at different temperatures were measured by a Physical Property Measurement System (PPMS) with the specimen size of 10 mm long and 5 mm wide. The current used during experimental is 5000 μA and the testing temperature range is from 50 K to 350 K. The measured resistance was translated to resistivity with the length and cross-sectional area of the test samples.

A custom-fabricated equipment was used to perform the current density testing on all the composites. It consists of a quartz tube and a Shekonic TN-KG Z01 high-frequency switching DC power. The composites were put into the tube and connected to the DC power via conductor. Under argon atmosphere with the flow rate of 500 sccm, the experiments were carried out by sequentially stepping up the current and simultaneously recording the voltage. Resistance at every voltage step, computed according to the Ohm's law, was translated to resistivity with knowledge of length and cross-sectional area of the test samples. The cross-sectional area was also used to compute the applied current density at every stage of experiment. Each specimen was about 50 mm long and 2 mm wide. In order to analyze the effect of specimen size on the test results of current density, a shorter size of 20 mm long and 2 mm wide was also used for test. The testing was carried out twice.

The heat-conducting property was qualitatively studied by thermal imaging method, in which the comparative experiments were conducted on the as-prepared composite specimen and two pure commercial copper sheets. The key to this method is to detect the distribution of temperature in the surface of the sheet specimen, and then to calculate temperature difference between the heating center and the edge of the specimen. To increase the accuracy of temperature difference detection, a specimen with a suffi-

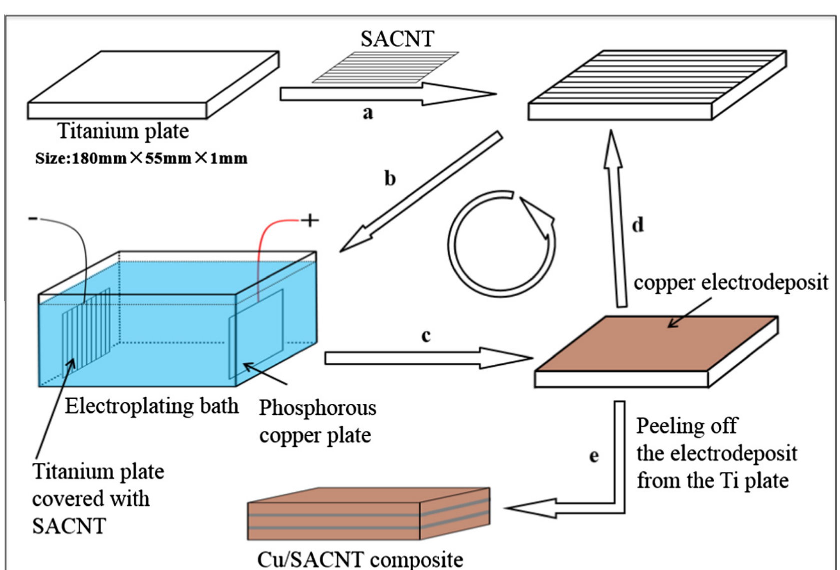

Fig. 1. Schematic process of the preparation of Cu/SACNT composite. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)