Tribological properties of carbon-nanotube-reinforced copper composites

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Received 9 October 2000; accepted 1 February 2001

Tribological properties of carbon-nanotube-reinforced copper composites were investigated using a pin-on-disk test rig under dry conditions. The composites containing 4–16 vol% carbon nanotubes (CNTs) were fabricated by a powder-metallurgy technique. The tests were carried out at normal loads between 10 and 50 N, and the effect of volume fraction of CNTs on tribological behavior of the composites was examined. The composites revealed a low coefficient of friction compared with the copper matrix alloy. Due to the effects of the reinforcement and reduced friction, the wear rate of the composites decreased with increasing volume fraction of CNTs at low and intermediate loads. The composites with a high volume fraction of CNTs exhibited high porosity and their wear resistance decreased under high-load conditions.

KEY WORDS: carbon-nanotube-reinforced copper composites; coefficient of friction; wear rate

1. Introduction

Carbon nanotubes (CNTs) are increasingly attracting scientific and technological interest by virtue of their properties and potential applications [1]. Their high length : diameter ratio, strength, elastic modulus [2,3], flexibility [4] and unique conductivity [5] along with other properties have led to the use of the carbon nanotube as a novel fiber for a variety of composite materials. Kuzumaki et al. [6] characterized the processing and the mechanical properties of a carbon-nanotube-reinforced Al composite prepared by hot pressing followed by hot extrusion. This work indicated that the carbon nanotubes in the composites are not damaged during the composite preparation and that no reaction products at the nanotube/Al interface are visible after annealing for 24 h at 983 K. The strength of the composites is slightly affected by annealing at 873 K. Although some investigations [7,8] have been conducted on processing technology, microstructure and mechanical properties of carbon-nanotube-reinforced composites, very few studies on tribological properties of the composites have been reported [9].

It is expected that the metal-matrix composites reinforced by nanotubes would have high strength and wear resistance [9]. In general, the tribological properties of composites are often affected by microstructures in the composites [10–12]. To improve the interfacial bonding strength, in the present work, a nickel layer was plated onto the surfaces of carbon nanotubes by electroless plating. The tribological properties of carbon nanotube–copper composites fabricated by a powder-metallurgy technique are evaluated.

2. Experimental

2.1. Preparation of composites

The multi-walled carbon nanotubes used in this work were produced by the catalytic decomposition of acetylene over mesoporous silica containing cobalt nanoparticles, which were prepared by a sol–gel process. An acetylene–nitrogen mixture (C 2 H 2 :N 2 = 1 : 3) was introduced into the quartz chamber at a flow rate of 400 ml min⁻¹ at 750 °C for 20 min, and carbon nanotubes were formed on the catalyst substrates. After clipping in HNO 3 and HF solutions, washing with distilled water and drying at 120 °C, the silica, cobalt nanoparticles and amorphous carbon were removed. CNTs (with length 2–10 µm and diameter 15–20 nm, density 2.0 g cm⁻³) with 95% purity were obtained (figure 1(a)).

To improve the dispersion, the CNTs were milled for 8 h in an organic liquid with a Planetary ball mill machine. The CNTs were then coated with nickel in order to ensure good wetting of the CNTs by the matrix alloy. Before electroless plating, the CNTs were pretreated in a sensitizing solution of 0.1 M SnCl 2–0.1 M HCl for 30 min and in an activating solution of 0.0014 M PdCl 2–0.25 M HCl for another 30 min. Then the activated CNTs were washed with distilled water and introduced into an electroless nickel bath. The composition of the electroless nickel bath solution and the operation conditions are shown in table 1. A TEM photograph of the nickel-coated CNTs, which were obtained by stirring the nickel bath solution for 15 min, is shown in figure 1(b). After the electroless plating process, the surfaces of the CNTs were essentially covered by the nickel coatings.

Copper powder (>99.5%) of average size 70 µm was employed as the matrix alloy. Five composite specimens, containing 0, 4, 8, 12 and 16 vol% CNTs, respectively, were
fabricated by the powder metallurgy (PM) technique. The powders of copper- and nickel-coated CNTs were mixed for 30 min in a ball mill. After mixing, the powder mixtures were isostatically pressed at a pressure of 600 MPa at 100 °C for 10 min under vacuum (10^-2 Pa), and then isothermally sintered at 800 °C for 2 h. Bulk hardness of the composites was measured using a Rockwell B tester, at a load of 15 kg. By measuring the powder density and composite density using a density meter, the porosity of the composites can be determined. Wear specimens of carbon nanotube–copper composites with a cross-sectional area of 20 × 20 mm were machined from these sintered materials. All specimens were polished with 1000-mesh SiC paper and degreased with acetone before each experiment.

2.2. Friction and wear tests

The friction and wear tests were performed under dry conditions in accordance with ASTM G99-90 standards using a pin-on-disk test rig which is similar to the one used by Poonawala et al. [13]. The composite specimen was mounted as the disk on the rotating lower holder. The spherical diamond pin with a radius of 0.2 mm was normal to the rotating disk. The experiments were conducted at a sliding speed of 4.7 × 10^-3 m s^-1 and at applied loads between 10 and 50 N. Weight loss was measured with an analytical balance at intervals of 1 m throughout the test. The coefficient of friction was calculated by dividing the friction force which was recorded on line via torque as measured by the strain gauge, by the applied load. In order to take repeatability into account, the test results for coefficient of friction and wear rate under steady-state sliding were obtained from the average of three readings.

3. Results and discussion

Table 2 lists the hardness and porosity of unreinforced copper alloy and carbon-nanotube-reinforced copper composites. The porosity of the composites remained the same value at lower volume fraction of CNTs, but then increased sharply above 12 vol% CNTs. As result of the effects of reinforcement and porosity, the hardness of the composites first increased with increasing volume fraction then decreased with further increase in volume fraction. The composites with 12 vol% CNTs exhibited the highest value of hardness.

The variation of average coefficients of friction versus volume fraction of CNTs for steady-state sliding at various loads is plotted in figure 2. The values of coefficient of friction for the composites decreased with increasing applied load. As compared to the unreinforced copper matrix alloy, the carbon-nanotube-reinforced copper composites revealed low values of the coefficient of friction, which were between 0.096 and 0.19. It is evident from this figure that the coefficient of friction for the composites with higher volume fraction of CNTs was slightly lower than that for the composites with lower volume fraction of CNTs. This observation suggests that an increase in surface fraction of CNTs reduces the direct contact between the metallic matrix and diamond pin and modifies the friction due to self-lubrication of CNTs,