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Hot extrusion to manufacture the metal matrix composite of carbon nanotube and aluminum with excellent electrical conductivities and mechanical properties

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ABSTRACT

New metal matrix composite (MMC) manufacturing process to produce the compound material of carbon nanotube (CNT) and aluminum is proposed. This process is capable of MMC manufacturing with excellent electrical and mechanical properties, by controlling powder compacting stress and the temperature of the hot extrusion to integrate of CNT and Al powder. The crystalline of CNT in the MMC was systematically investigated, and it was confirmed that the crystalline of CNT was maintained without receiving the influence of heat by the hot extrusion. The new MMC manufacturing process might be an ideal process for an electric conductivity increase.

1. Introduction

Electric wire is an essential component in automobiles, home appliances and high-voltage lines. The material used for the electric wire in high-voltage lines, fuel-cell vehicles and hybrid vehicles is gradually changing from copper to aluminum to decrease the weight of vehicles [1]. However, the strength and electrical conductivity of aluminum are lower than those of copper. Therefore, if an aluminum electric wire that has high strength and high electrical conductivity can be manufactured, marked weight reduction of vehicles and compact high-voltage lines will be realized.

When alloying elements are added to aluminum, the strength of aluminum typically increases. However, the electrical conductivity of aluminum is markedly decreased, as shown in Fig. 1. The electrical conductivity (%IACS) was calculated by dividing the measured resistance by the international annealed copper standard resistance. To overcome this decrease in electrical conductivity while maintaining lightness, a material with greater strength and higher electrical conductivity is strongly required for mixing with aluminum. At present, carbon is the focus of attention as the most effective material for realizing lightness and high strength, as typified by CFRPs with carbon fibers. Research on the machining [2] and assembly [3] of CFRPs has been reviewed in CIRP annals.

On the other hand, since the discovery of carbon nanotubes (CNTs) by Iijima [4], they have attracted interest as next-generation reinforcement materials, owing to their desirable mechanical and electrical properties. Moreover, Li et al. measured the current–voltage characteristics of a single multiwall CNT at room temperature and observed high electrical conductivity with a range of ±0.2 V [5]. Many researchers have attempted to fabricate metal matrix composites (MMCs) to realize new engineering materials containing CNTs, and several processes for manufacturing MMCs were summarized in a review by Bakshi et al. [6]. However, these MMC manufacturing processes involve severe conditions such as powder sintering for a long time at a high temperature, making it difficult to maintain the structure of CNTs. Reinikainen et al. clarified the behavior of a copper specimen formed by hot extrusion with rapid heating by using the finite-element method [7]. If CNTs and aluminum can be compounded by a hot-treatment process for a short time to maintain the structure of the CNTs, a new manufacturing process may be realized for producing MMCs with sufficient strength and high electrical conductivity. A new MMC manufacturing process involving

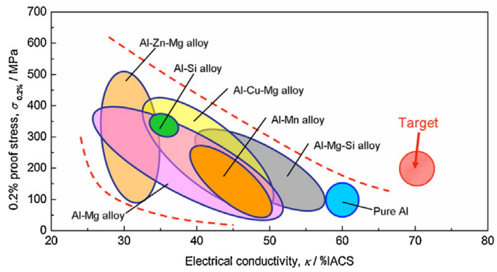

Fig. 1. Relationship between electrical conductivity and 0.2% proof stress of Al alloys.

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hot extrusion for producing CNT/Al composite materials is proposed in this paper. With the aim of controlling the electrical properties of MMC specimens, we performed hot extrusion without additional heating before extrusion, and we demonstrated the possibility of obtaining MMC specimens with high strength and electrical conductivity. We also investigated the change in the crystallinity and structure of the CNTs during hot extrusion.

2. Experimental

2.1. MMC manufacturing process and materials

Pure Al powder was used in this investigation. The chemical composition of the pure Al powder is shown in Table 1. The components of the pure Al powder were analyzed using inductively coupled plasma. As shown in the table, the purity of the Al powder was 99.9%.

Table 1
Chemical composition of the pure Al powder (mass%).

	O	Fe	Si	Cu	Mn	Al
Pure Al powder	0.021	0.031	0.012	0.002	0.002	Bal.

Fig. 2 shows a schematic illustration of the manufacturing process for MMCs in this study. The initial pure Al powder, which was manufactured by the atomizing method by Kojundo Chemical Laboratory Co., Ltd., has an average particle diameter of 50 μm. The multiwall carbon nanotubes were manufactured by Hodogaya Chemical and had the average diameter, length and number of layers of 65 nm, 10 μm and 70, respectively.

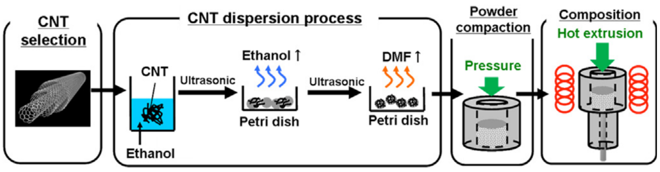

Fig. 2. Schematic illustration of setup during MMC manufacturing process.

Firstly, the multiwall carbon nanotubes (0.06 g) in ethanol (190 ml) were agitated by ultrasonic treatment for 30 min at 20 kHz. Here, the volume of CNTs used in MMC corresponds to a pure Al powder of 0.1 vol%. Pure Al powder was added to the liquid containing dispersed multiwall carbon nanotubes, then the ethanol was evaporated using an evaporator in vacuum. Two milliliters of *N*-dimethylformamide was added dropwise to the multiwall carbon nanotubes and pure Al powder during the ultrasonication. Here, a Petri dish was used to suppress the separation caused by the difference in specific gravity between the multiwall carbon nanotubes and the Al powder. Secondly, the powder was placed in a billet and then compacted at room temperature. The conditions of powder compaction and hot extrusion are given in Table 2. The powder compressive stress was varied from 62 to 748 MPa.

Table 2
Powder compaction and hot extrusion conditions in this study.

Compressive stress in powder compacting [MPa]	62, 187, 374, 561, 748
Ram speed r [mm/s]	12
Process temperature [K]	773

Finally, the mixed powder was sintered and subjected to plastic deformation by hot extrusion to control the strength and electrical conductivity of the MMC to the target values shown in Fig. 1. The diameter of the compacted powder specimen was 10.0 mm, whereas the diameter of the rod specimen after hot extrusion was 4.0 mm; thus, the extrusion ratio was 6.25. The ram speed and temperature during hot extrusion were 12 mm/s and 773 K, respectively. The ram speed was calculated from the pushing length and extrusion time.

2.2. Evaluation method

The electrical conductivity of hot-extruded specimens was measured by a four-terminal method at room temperature. Electrical conductivity was measured using a device with a measurement accuracy of ±0.01%. The spacing between terminals was 20 mm and the measurement current was 20 mA.

A tensile test was carried out on the MMC product formed by the proposed manufacturing process at a nominal strain rate of $1.5 \times 10^{-3}\ s^{-1}$ at room temperature. The tensile test specimens were dumbbell-shaped with dimensions of 2.4 mm × 1.0 mm × 1.0 mm, complying with the ISO 6892-1 (2009) standard, and the strength was measured using an Instron-type testing machine.

The multiwall carbon nanotubes were evaluated at various stages in the manufacturing process for the MMC. The pure Al used in the manufacturing process was dissolved for 8 h in a mixture of acid (hydrochloric acid: hydrogen peroxide: pure water = 2:1:1), and the CNTs at various stages were extracted from the MMC specimens. The shape and structure of the CNTs at various stages during the manufacturing process were observed by scanning transmission electron microscopy at 200 kV.

3. Results and discussion

3.1. Unique electrical and mechanical properties of MMC specimens

The change in the electrical conductivity of hot-extruded specimens at various compressive stresses is shown in Fig. 3. The reproducibility experiments on electrical conductivity were conducted using three specimens under each extrusion condition. The electrical conductivity of the hot-extruded specimens of pure Al powder increased with increasing compressive stress, and reached approximately 61.77%IACS at a compressive stress of 561 MPa. Note, however, that the electrical conductivity of the hot-extruded specimens of pure Al powder did not exceed that of a pure Al cast specimen. On the other hand, the electrical conductivity of a hot-extruded specimen of pure Al powder/CNTs subjected to a compressive stress of 561 MPa was approximately 64.21%IACS. The electrical conductivity of this pure Al powder/CNT specimen at a compressive stress of 561 MPa was 5% higher than that of the pure Al powder specimen, and exceeded that of the pure Al cast specimen. We have not yet clarified the reason for the increase in the electrical conductivity of the hot-extruded specimens of pure Al/CNTs and pure Al powder at a compressive stress of 740 MPa.

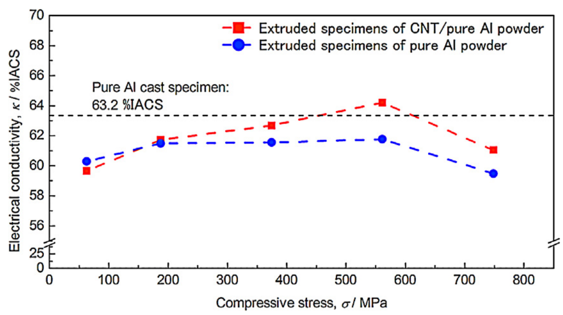

Fig. 3. Change in electrical conductivity of hot-extruded specimens of pure Al powder and pure Al powder/CNT at various compressive stresses.

Generally, the electrical conductivity of metals tends to decrease upon mixing with other elements. The electrical conductivities of MMCs with CNTs contents from 3.0 to 3.5 vol%, were similar to those of the bulk specimens of parent metal and alloy materials [8,9]. However, the electrical conductivities of MMCs in the present study exceeded those of pure Al bulk specimen and hot-extruded specimen of pure Al