Fabrication of AL6061-CNT Composite by Mechanical Alloying followed by Semi-Solid Powder Processing

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Abstract
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Keywords
composite materials, manufacturing, carbon nanotubes

Disciplines
Manufacturing | Metallurgy

Comments

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FABRICATION OF AL6061-CNT COMPOSITE BY MECHANICAL ALLOYING FOLLOWED BY SEMI-SOLID POWDER PROCESSING

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ABSTRACT
Carbon nanotubes (CNTs) have been widely investigated as a reinforcement material to improve the mechanical, electrical and thermal properties of composite materials. Various routes have been employed to fabricate aluminum-carbon nanotube (Al-CNT) composites in the past few years. However, uniform distribution of CNTs in the metal matrix is still challenging. In this paper, a novel semi-solid powder processing (SPP) was used to incorporate CNT uniformly into the Al6061-CNT composite. Al6061-CNT powders mechanically alloyed for different durations were also examined to understand how the CNTs were dispersed in the Al6061 powders. As-received CNT cluster balls were crushed into dense thin CNT layers during mechanical alloying. As mechanical alloying time increased, CNTs were dispersed in the Al6061 particles. Well-densified microstructures with severely deformed grains were observed in the Al6061-CNT composite.

INTRODUCTION
In the past few years, research in incorporating carbon nanotubes (CNTs) into the metal matrix has increased due to the promising mechanical, thermal and electrical properties of CNTs. However, achieving a uniform CNT distribution in the composite is still challenging. High initial cost for plasma spray forming [1, 2], low structure controllability for friction stir processing [3], high aluminum carbide formation in squeeze casting [4], and post-processing needed in sintering [5] have also been noted.

Semi-solid Powder Processing (SPP) combines the benefits of the semisolid forming and powder metallurgy [6-8]. It is capable of tailoring the composite properties by mixing desired powders or fibers and eliminating the process steps required in powder metallurgy routes. A summary of various processing routes of SPP is shown in Figure 1 [9-11]. Four processing steps are generally involved in the SPP: powder preparations, pre-compaction of the powders, heat-up, and formation in the semisolid state [9, 10, 12-14]. The previous work demonstrated the potential of SPP in the fabrication of various metal composites [12, 15-20].

FIGURE 1: PROCESS ROUTES OF VARIOUS SEMISOLID POWDER PROCESSING

In this paper, SPP was employed to synthesize the Al6061-CNT composite. Mechanical alloying was utilized to disperse the CNTs into the Al6060 particles [21-23]. Mechanical alloying time varied from 10 minutes to 3 hours.

EXPERIMENTAL SETUP
Series of the Al6061 (Valimet Inc.) particles and 1 wt.% multi-walled carbon nanotubes (NanoLab) were prepared by mechanical alloying (SPEX 8000M, 1000 rpm) for 10 mins, 30
mins, 1 hr, 2 hr, and 3 hrs, respectively. The mean size of the Al6061 powder used in this study was 13.82 μm, and CNTs were 20–50 nm in diameter and 5–20 μm in length. Al6061-1.0 wt.% CNT composite was fabricated with powders by mechanical alloying for three hours.

The experimental setup for the SPP is shown in Figure 2. The load and displacement of the upper ram were controlled and measured by the materials testing system (TestResources Inc., 800LE), while the temperature of the setup was controlled by the furnace (Applied Test System Inc). The temperature and pressure profiles used in the experiments are shown in Figure 3. Experimental settings are summarized in Table 1. For comparison, Al6061 composites without CNTs were fabricated from two Al6061 powder batches: mechanical alloyed for three hours and as-received powder.

The microstructures of the samples were observed with an optical microscope (Zeiss, Axiovert 200M) and a scanning electron microscope (JEOL JSM-606LV). A Siemens D-500 X-ray diffraction system was used to obtain the X-ray diffraction pattern of the composite sample.

![Figure 2: Experimental Setup for Semi-Solid Powder Processing](image1)

![Figure 3: Heating and Pressure Profile Used in the Experiments](image2)

<table>
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<th>TABLE 1: EXPERIMENTAL SETTINGS</th>
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<tr>
<td>Forming Pressure (MPa)</td>
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<tr>
<td>Pressure Holding Time (min)</td>
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<td>CNT Loading (wt%)</td>
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<td>Punch Velocity (mm/s)</td>
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<td>Liquid Fraction of Al6061 at 640°C</td>
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<td>Mean size of Al6061 Powder (μm)</td>
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**RESULTS AND DISCUSSION**

**Powder Preparation**

The SEM images of as-received CNTs and Al6061-CNT powders mechanically alloyed for different durations are shown in Figure 4. In Figure 4(b), as-received CNTs are strongly entangled and are clustered into a form of spherical structure with diameter of 1–7 microns (Figure 4(a)). After 10 minutes of mechanical alloying, most of the CNT balls were crushed and attached to the Al6061 powder surface (Figure 4(c)). From Figure 4(d), 30 minutes of mechanical alloying can disperse most of the CNTs. Only limited amount of CNT thin-dense layers were observed on the Al6061 powder surface. Mechanical alloying for another 30 minutes achieved a good CNT dispersion on the Al6061 particle surface (Figure 4(e)). However, as shown in Figure 4(f), CNT clusters covered by Al6061 layers were also observed. With the increase of mechanical alloying time, the visible CNTs on the Al6061 particle surface gradually decreased due to the merging of Al6061 particles (Figure 4(g)). After three hours of mechanical alloying, CNTs could be rarely found on the surface (Figure 4(h)).

From the observations, the mechanical dispersion of CNTs occurs in two stages. First, the CNTs spherical structures are crushed by colliding with the ceramic balls. For the case studied in this paper, this happened in the first 30 minutes. Second, the crushed CNT thin layers are dispersed into separate CNTs by the shearing action from ceramic balls and/or the Al6061 particles.

Due to the cold-welding during the mechanical alloying, the size of the Al6061 particles increased [22]. Once the CNT clusters are covered by thick layers of Al6061, the dispersion may become difficult (see Figure 4(f)). Therefore, the CNTs embedded inside the agglomerated Al6061 are unlikely to be further dispersed by mechanical alloying process.
Microstructures

Microstructures of the samples fabricated from Al6061-1.0 wt.% CNT mechanically alloyed for 3 hours, Al6061 powder mechanically alloyed for 3 hours, and as-received Al6061 powder are shown in Figure 5. It can be observed in Figure 5(a) that the Al6061-CNT composite fabricated by SPP showed a well-densified microstructure. Layered Al6061 grains were observed in Al6061-CNT as shown in Figure 5(b). The thickness of the Al6061 layers ranges from 1.04 μm to 3.96 μm. Compared with as-received Al6061 sample in Figure 5(d), smaller but severely deformed grains were observed due to the mechanical alloying procedure.

Mechanical alloying refined the grains in the metal composites [7], in both the Al6061-CNT composite and Al6061-only composite. During the mechanical alloying, the particle size increased significantly, while new grains formed during the consolidation process due to high energy input by the mechanical alloying procedure. As shown in Figure 5(c),
the deep black etched lines were boundaries of the mechanically alloyed Al6061 particles. The newly formed grains as shown in (Figure 5(c)) were significantly smaller than as-received Al6061 mechanically alloyed composites (Figure 5(d)).

Mechanical Properties

The hardness of Al6061 composite samples made from as-received Al6061-only powder, Al6061-only powder with three hours of mechanical alloying, and Al6061-1.0 wt.% CNT was 43.83 HV, 61.50 HV and 76.50 HV, respectively. We speculate that four hours of mechanical alloying increased the composite hardness by 40.3%, and 1.0 wt.% CNT addition improved it by additional 33.7%.

![Figure 6: Hardness composite with different experiment conditions](image)

**CONCLUSIONS**

Fully densified Al6061-1.0 wt.% CNT composite was successfully fabricated by SPP. The grains deformed severely due to the long mechanical alloying time. The hardness of the Al6061-CNT composite is improved by 74.0% compared with the composite synthesized from as-received Al6061 powder. It seemed that adding the CNTs resulted in fine microstructure. In addition, the CNT dispersing process by mechanical alloying was understood. The CNT cluster balls were first crushed by collision with the ceramic balls, and further CNT dispersion occurred by the shearing action of other particles. The agglomeration during mechanical alloying may prevent full dispersion of CNTs in the composite.

**REFERENCES**


