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Mechanical and thermal properties of nanocarbon-reinforced aluminum matrix composites at elevated temperatures

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ABSTRACT

This study evaluated the mechanical and thermal properties of aluminum alloy 2024 (Al2024) matrix composites reinforced with multi-walled carbon nanotube (MWCNT) or few-layered graphene (FLG) in the temperature range of 250–430 °C. The Al2024/MWCNT and Al2024/FLG composites were fabricated using powder metallurgy, and the associated microstructures were observed. At 350 °C, both composites maintain high yield stress about 110 MPa, since uniform dispersion of the nano-scale reinforcements has a strong interface, hinders the dislocation movement and eutectic phase coarsening and severe softening of the matrix. The composites also show a low thermal expansion coefficient of ~$18\times10^{-6}/K$. The results are respectively over ~2.5 times higher strength and ~20% lower CTE than those of commercial Al alloy used as piston material ($AlSi_{12}CuMgNi$).

1. Introduction

The simultaneous increase in the demand for vehicle applications, improved fuel economy, and CO_2 emissions, has led to the steady increase in developmental efforts to achieve weight reduction [1–3]. Better engine combustion efficiency provided by a turbocharged direct injection system, motor-driven power steering, and a selective controlled engine with an idle stop and go system can reduce the peak power of engine and frictional loss [4,5]. Therefore, several studies have been conducted to substitute conventional steel and cast irons with lightweight metals [6–9]. Among the applications, the driving condition of an engine's piston is most affected by severe environmental factors, such as high combustion pressure and temperature [6,10]. Therefore, materials that are used in engines should have high strength and low thermal expansion at high temperatures [4,5].

Aluminum (Al) is one of the promising candidates for automobile applications because of its good formability and high corrosion resistance compared with other nonferrous metals. Therefore, Al and its alloys are fabricated using casting or powder metallurgy (P/M) with addition of alloying elements or reinforcements, which can facilitate enhancing the metal's mechanical properties [11–16]. Among the commercial Al casting alloys, Al-Si alloys are commonly used because of their good strength and low coefficient of thermal expansion (CTE) [17]. However, the addition of alloying elements to improve and adjust the properties depending on the specific need (for piston or engine parts) leads to shrinkage porosity and large or segregated intermetallic phases, which can be detrimental to high-temperature strength [18,19]. For instance, the coarse plate-like structure of Al-Si can promote an inherent brittle eutectic phase and form Al-Cu intermetallics, which leads to the formation of defects [20]. Furthermore, the presence of a nonconductive eutectic phase and microvoids from shrinkage porosity affects the CTE [21].

To overcome the limitations of the high-temperature mechanical properties of currently used casting Al alloys, nanocarbon materials (i.e., fullerene, carbon nanotube (CNT), graphene, etc.) reinforced Al or its alloy matrix nanocomposites have been fabricated owing to their excellent properties [22–25]. Among the nanocarbon materials, CNT and graphene show outstanding mechanical properties (Young's modulus ~1 TPa and tensile strength ~30 GPa), low thermal expansion (negligible at 25 °C), and low density; therefore, they are widely used as reinforcing agents to add to the greater strength and lower CTE of Al-matrix nanocomposites [26–31]. Moreover, fabrication of Al-matrix nanocomposites reinforced with CNT or graphene has been successfully achieved using P/M because of property of the reinforcements of uniform dispersion without destruction to the molecular structure [22–24]. However, limited studies have been conducted on the use of

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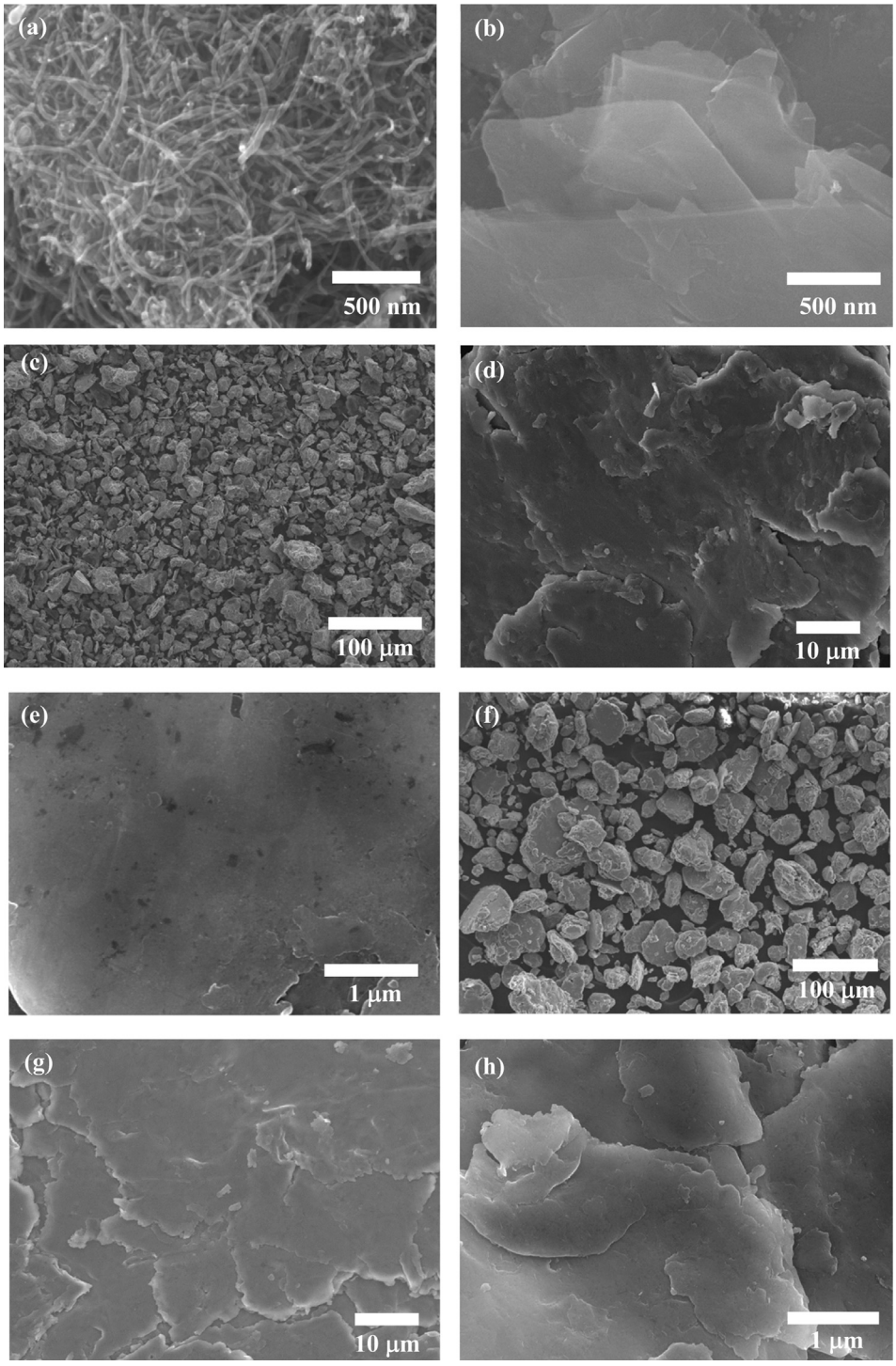

Fig. 1. SEM images of (a) MWCNT, (b) FLG and ball-milled composite powders; (c) Al2024/MWCNT, (d) the enlarged view of (c), (e) the magnified image of (d); (f) Al2024/FLG, (g) the enlarged view of (f), (h) the magnified image of (g).

powder-formed CNT- or graphene-reinforced Al-matrix nanocomposites as piston materials.

To develop materials with high strength and lower CTE at elevated temperatures, the Al alloy 2024 (Al2024) matrix was reinforced with multi-walled carbon nanotubes (MWCNT) or few-layer graphene (FLG) by using P/M and ball-milling techniques, respectively. The ball-milled composite powders were then hot-pressed for consolidation. The microstructure, compressive behavior, and CTE of the Al2024-matrix containing MWCNT or FLG composites were investigated at temperatures up to 430 °C.

2. Experimental

Commercially available Al2024 powder (99.5% pure, diameter <120 μm, and weight percentage of 4.0 Cu, 1.5 Mg, and 0.5 Mn; supplied from Al Co., LTD.) was used as the matrix. MWCNT (~20 nm in diameter and ~5 μm in length; supplied from ACN Co. LTD., South Korea) and FLG (6–8 nm thick with a typical specific