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Original Research Article

Mechanical properties and abrasive wear behaviors of in situ nano-TiC_x/Al–Zn–Mg–Cu composites fabricated by combustion synthesis and hot press consolidation

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ABSTRACT

The in situ nano-TiC_x/Al–Zn–Mg–Cu composites with different TiC_x content (20, 25 and 30 vol.%) were successfully fabricated by combustion synthesis and hot press consolidation in Al–Ti–C/CNTs systems. The compressive properties and abrasive wear resistance of the composites improved with the increase in the TiC_x content. The transformation of carbon source from pure C black to the mixture of C black and CNTs to pure CNTs in Al–Ti–C/CNTs systems leaded to a significant improvement in the compressive properties and wear resistance of the composites as well as a significant decrease in the average size of TiC_x particles. The average size of the nano-TiC_x particles in 30 vol.% TiC_x/Al–Zn–Mg–Cu composite synthesized by the carbon source of CNTs reached 81 nm, moreover, the yield strength ($\sigma_{0.2}$), the ultimate compression strength (σ_{UCS}) and the fracture strain (ε_f) of the composite reached 597 MPa, 882 MPa and 21.7%, respectively.

1. Introduction

Al–Zn–Mg–Cu alloys are widely used in aviation, aerospace and defense fields due to its outstanding properties such as extremely high specific strength, high toughness and good mechanical properties [1–3]. However, their small ductility, low strength and poor wear and corrosion resistant hamper their applications. In the recent decades, many researchers focused on how to improve the strength and toughness by

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introducing the reinforcements of hard ceramic particles into Al alloy, such as SiC, TiC, TiB_2, B_4C and Al_2O_3 [4–10]. For instance, Guo et al. [11] introduced 35 vol.% TiC with a particle size of 2–3 μm into Al-Si-Cu alloy by gas pressure infiltration. They reported that the composites obtained extremely high compressive strength and elastic modulus. Azimi et al. [12] reported that Al–Zn–Mg–Cu alloy reinforced with TiC particles exhibited high mechanical properties and micro-hardness. Therefore, TiC is a good candidate of reinforcement for Al alloy.

However, it is necessary to point out that the Al matrix composites reinforced with TiC_x particles often possess terrible ductility, which limits their further applications in engineering [4,7,11,12]. Generally, nano-sized particles can significantly enhance the strength of metal-matrix composites without reducing the ductility [6,8]. Nevertheless, nano-sized particles that tend to form micro-clusters mostly due to attractive Van der Waals forces between nano-sized particles [2,5,6] are difficult to disperse uniformly in metal matrices.

It is reported that the metal matrix composites fabricated by combustion synthesis and hot press consolidation successfully overcome these shortcomings and exhibit a clearer interface between reinforcement and matrix, as well as smaller sized reinforced particles with homogeneous dispersion [4,13,14]. However, up to now, there were hardly reports on the in situ nano-TiC particles reinforced Al–Zn–Mg–Cu composite, and on the effects of the content of the nano-sized ceramic particles on the compression properties and wear resistance abilities of the composites. In the present paper, the Al–Zn–Mg–Cu composites reinforced with 20–30 vol.% in situ nano-TiC_x particles were fabricated by combustion synthesis and hot press consolidation in the Al–Ti–C systems with different carbon source. The effects of the carbon source in the Al–Ti–C reaction system and the content of nano-sized ceramic on the microstructures, compression properties and abrasive wear resistance of the nano-TiC_x/Al–Zn–Mg–Cu composites were investigated.

2. Sample preparation and testing

The raw materials used here were Al alloy powders (99 wt.% purity, ~48 μm), Ti powders (99.5 wt.% purity, ~25 μm), carbon nanotubes with a purity of 98 wt.% and dimensions of 10–20 nm in diameter and 20–100 μm in length, and carbon black (99 wt.% purity, ~0.1 μm). The chemical compositions of Al–Zn–Mg–Cu alloy were presented in Table 1. The Ti and carbon (carbon black or CNTs) powders with the atom ratio of 1:1 were mixed with the different content of Al alloy powders. The raw mixtures were mixed sufficiently by ball milling for 8 h and then cold pressed into cylindrical compacts (ϕ 29 mm × 38 mm). The reactants were placed in a homemade vacuum furnace. The chamber was heated at a speed of about 30 K/min and the temperature was measured by the thermocouples of Ni–Cr/Ni–Si. When the measured temperature abruptly rose rapidly, the reactant was ignited and then the compact was pressed quickly at the pressure of approximately 50 MPa for 20 s. Subsequently, the temperature of compacts cooled with the furnace to room temperature. The specimens of Al–Zn–Mg–Cu matrix alloy were also prepared by the same method. The nominal compositions of the composites were shown in Table 2.

The constituents of phase were identified by XRD (Model D/Max 2500PC Rigaku, Japan). The microstructures of the composites after being polished and etched by Keller's reagent were observed by SEM (Model Evo 18 Carl Zeiss, Germany). The synthesized TiC_x particles were extracted from the chippings of the composites which were immersed in 18 vol.% HCl aqueous solution. The morphologies of the TiC_x particles were examined by FESEM (JSM-6700F, Japan).

The cylindrical specimens (ϕ 3 mm × 6 mm) used for compression testing were tested by a servo hydraulic materials testing system (MTS 810, USA) with a strain rate of 10^{-4} s^{-1} at room temperature. The faces of the load of the specimens were polished to be parallel to each other before compression test. Four specimens of the Al–Zn–Mg–Cu alloy and nano-TiC_x/Al–Zn–Mg–Cu composites were tested to determine the compressive properties. The micro-hardness of Al–Zn–Mg–Cu alloy and composites was determined by a Vickers hardness tester (Model 1600-5122VD, USA) at the load of 3 N for 10 s and each sample was tested for 10 times. Abrasive wear tests were performed using a pin-on-disk apparatus with sliding distance of 24.78 m at room temperature. Polished specimens with dimensions of ϕ 6 mm × 12 mm were prepared for the tests and the surfaces of ϕ 6 mm were used as the wear surfaces. In terms of the dimensions of the wear surfaces, the large applied loads are not suitable for the abrasive wear tests and the loads of 10, 20 and 30 N are

Table 1 – Chemical compositions of the Al–Zn–Mg–Cu alloy (wt.%).

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
wt.%	0.4	0.5	1.2–2.0	0.3	2.1–2.9	0.14–0.28	5.1–6.1	0.02	Balance

Table 2 – Characteristics of the samples.

Samples	Designed composition	Reaction system
Al alloy	Al–Zn–Mg–Cu alloy	–
20A	20 vol.% TiC/Al–Zn–Mg–Cu	Al–Ti-CNTs
25A	25 vol.% TiC/Al–Zn–Mg–Cu	Al–Ti-CNTs
30A	30 vol.% TiC/Al–Zn–Mg–Cu	Al–Ti-CNTs
30AB	30 vol.% TiC/Al–Zn–Mg–Cu	Al–Ti–C/CNTs (the molar ratio of carbon black/CNTs = 1:1)
30B	30 vol.% TiC/Al–Zn–Mg–Cu	Al–Ti–C