Journal of Alloys and Compounds 764 (2018) 460–466

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Aging behavior of Be/6061Al composite fabricated by hot isostatic pressing technique

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A R T I C L E I N F O

Article history:
Received 13 April 2018
Received in revised form
6 June 2018
Accepted 12 June 2018

Keywords:
Aging
Be/6061Al composite
Precipitates

A B S T R A C T

The aging behavior of Be/6061Al composites cannot indiscriminately copy the aging behavior of the 6061Al matrix alloy. In this study, the aging behavior of Be/6061Al composite (62% mass fraction of Be) fabricated by powder metallurgy technique was investigated by Micro Vickers hardness measurements, HRTEM and DSC experiments. Subsequently, the corresponding precipitation mechanism was discussed in detail. It was found that Be/6061Al composite exhibited an accelerated age hardening phenomenon as high density dislocations were incorporated by Be particles. The aging precipitation sequence of Be/6061Al composite was similar to 6061Al alloy, but the formation of GP zone was suppressed which can be attributed to the decrease of vacancy concentration caused by Be/Al interfaces and the segregation of Mg and Si on Be/Al interfaces.

1. Introduction

The aerospace industry is continually searching for ways to reduce the weight of its products. One of the most common ways for engineers to reduce weight is to make their products out of low-density alloys or engineering composites with very high specific strength and stiffness. Beryllium metal exhibits low density, high stiffness and low thermal expansion coefficient, which is particularly suitable for aerospace applications. Unfortunately, beryllium is intrinsically brittle at room temperature, which limits its use in many structural applications. Aluminum forms no intermetallic compound with beryllium and neither does aluminum exhibits significant solid solubility in beryllium nor beryllium in aluminum [1,2]. Beryllium aluminum composites have been under development for approximately 1961. Properties of a series of composites containing 24 wt% to 43 wt% Al were reported by Fenn [3]. The most common composition of beryllium aluminum contains 62 wt% beryllium and 38 wt% aluminum [4], which is known as Lockalloy or AlBeMet 162. The beryllium content was chosen to give an elastic modulus equivalent to that of steel (2.1×10^5 MPa). This composite is used in several aerospace applications, principally because of its good extrudability, ease of machining, better formability, and generally better fabricability than unalloyed beryllium. Compared with aluminum and titanium alloys, AlBeMet 162 was superior in potential performance for all stiffness-limited components and was only slightly lower than titanium for strength-limited designs, making it an excellent candidate in aerospace applications to reduce weight and dramatically increase the performance of stiffness-driven components [5–7].

Alloying elements such as Mg and Sc were added into beryllium aluminum composites to improve the mechanical properties or corrosion-electrochemical behavior [8–11]. Selecting 6061Al alloy instead of pure aluminum as the matrix could improve mechanical properties of beryllium aluminum composites [12]. The microstructure of powder metallurgy Be/6061Al composites consists of Be phase and Al rich phase. So Be/6061Al composites can be treated as beryllium particles reinforced 6061Al matrix composites. Compared with beryllium aluminum composites, the yield strength of Be/6061Al composites with same Be content increased dramatically after artificially aging treatment, which was mainly attributed to the precipitate strengthening in 6061 Al matrix [12].

The aging behavior of 6061Al alloy has been widely investigated by many groups around the world. The aging precipitation sequence of 6061Al alloy can be described as: supersaturated solid solution (SSS) → clusters of the magnesium and silicon → Guinier-Preston (GP) zones → β″ needles → β′ rods → Type A and Type C lath-shaped precipitates → β plates, some of which might be absent in the different conditions, viz., different material and aging temperature [13–17]. The aging behavior of composites which selected 6061Al alloy as matrix also has been studied. Zhao et al. [18] found

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https://doi.org/10.1016/j.jallcom.2018.06.124

that the addition of Al_3BC particles in 6061Al alloy accelerated the aging kinetics but Chu et al. [19]found that the aging responses of 6061Al composites were slightly weakened by the introduction of 0.3 μm Al_2O_3 particles. Besides, some reinforcements not only changed the precipitation kinetics, but also altered the aging sequence of the matrix. Cui et al. [20]found that for 55 vol% SiC_p/Al-Mg-Si composite, only one visible peak was observed, due to the formation of GP zones, β″, β′ and Type A precipitates, which was different from Al-Mg-Si alloy. Dong et al. [21]found that the precipitation sequence of 6061Al was changed after the addition of high content SiC nanowires. Chen et al. [22]proposed that the particles such as Y_2O_3 and TiC inhibited the formation of Mg–Si clusters and GP zones. So the incorporation of reinforcements in the 6061Al matrix significantly changed the thermal response of the composites and the reinforcements, which effected the precipitation kinetics of 6061Al matrix composites during the aging treatment.

Beryllium aluminum composites can be treated as beryllium reinforced aluminum matrix composites. Casting [8], powder metallurgy technique [23] and pressure infiltration method [24–29] have been adopted to prepare aluminum matrix composites. In our previous work, Be/6061Al composites with 62 wt% Be were successfully prepared by hot isostatic pressing sintering technology [12]. The microstructure and mechanical properties of Be/6061Al composites were studied. The yield strength of Be/6061Al composites with 62 wt% Be was dramatically improved after artificially aging treatment. However, there are few reports on the aging behavior of Be/6061Al composites. The precipitation sequence and precipitation kinetics of Be/6061Al composites are still unknown. The aging behavior of Be/6061Al composites cannot indiscriminately copy the aging behavior of the 6061Al matrix alloy. In this paper, the aging behaviors of the Be/6061Al composite (62% mass fraction of Be) were studied by Micro Vickers hardness measurement. Precipitates in different aging stages were characterized by HRTEM analysis and the corresponding precipitation hardening mechanism was discussed in detail.

2. Experimental details

Both 6061Al alloy and Be/6061Al composite were prepared by a powder metallurgy process. Commercially available inert gas atomized powders of 6061 Al alloy (with Mg and Si as its major alloying elements) with an average size of 10 μm and pure beryllium powders prepared by impact grinding with an average size of 7~9 μm were selected as raw materials. The chemical composition of the powders was listed in Table 1. To obtain a more uniform composition, the powders of 6061Al alloy and pure beryllium were mixed by ball milling for 6 h in argon atmosphere. Then the powder blends were consolidated by cold isostatic pressing (CIP). After encapsulated and degassed to remove adsorbed species such as water vapor, the green compacts were sintered by hot isostatic pressing (HIP) at 650 °C and100 MPa for 10 min 6061Al alloy without Be reinforcement was also prepared by the same process to compare the aging behavior with Be/6061Al composite.

Both Be/6061Al composite and unreinforced 6061Al alloy were solution treated at 530 °C for 1 h. Then the samples were aging treated at 150 °C, 170 °C, 190 °C with different time ranging from 0 h to 18 h. Micro Vickers hardness was measured and the curves of the hardness vs. aging time were obtained to discuss the aging kinetic. The hardness was measured using a MH-5L hardness tester with a load of 100 g and a dwell time of 15s. The average of ten indentations distributed over the whole surface of each sample provided the data used to draw the hardness curves. The error in Micro Vickers hardness is not more than ±3%.

Thin foils for TEM analysis were prepared in a twin-jet electro polishing unit using a solution of nitric acid: methanol (1:3 by volume) at 25 °C, 20 V and a current of about 80 mA. Transmission Electron Microscope (TEM) experiment was carried out to observe the interface and precipitation in Be/6061Al composite using a Titan G2 60–300 spherical aberration corrected transmission electron microscopy with an accelerating voltage of 300 kV.

DSC was conducted under an argon atmosphere using a METTLER-1100LF system between 20 °C and 500 °C with a heating rate of 10 °C/min.

Great care was taken during all operations above because beryllium is highly toxic and beryllium is considered extremely hazardous to health when sufficient quantities of dusts, mists, or fumes containing particles small enough to enter the lungs are inhaled.

Table 1
Chemical composition of Be powders and 6061Al alloy powders, wt%.

	Al	Mg	Si	Fe	Cu	Be
powders of Be	0.04	0.05	0.04	0.06	0.02	Balance
powders of 6061Al	Balance	0.95	0.51	0.10	0.04	–

3. Results

3.1. Hardness measurements

Fig. 1 showed the hardness variations of Be/6061Al composite aged at 150 °C, 170 °C, 190 °C after solution treated at 530 °C for 1 h as a function of extending aging time. It could be seen that the hardness of Be/6061Al composite increased with the aging time, reached the peak aging and then began to decrease gradually, which suggested that the Be/6061Al composite underwent the processes of under-aged, peak-aged and over-aged. The peak-aged hardness level was 138HV, 150HV and 140HV at the aging temperature of 150 °C, 170 °C and 190 °C respectively. It was worth noting that the peak-aged time was 12 h, 8 h and 4 h at the aging temperature of 150 °C, 170 °C and 190 °C respectively, indicating that the peak-aged time was shortened with the increase of aging temperature.

The impacts of beryllium on the aging behavior of 6061Al alloy matrix were investigated through comparing the aging hardening curves with and without beryllium reinforcements. The two

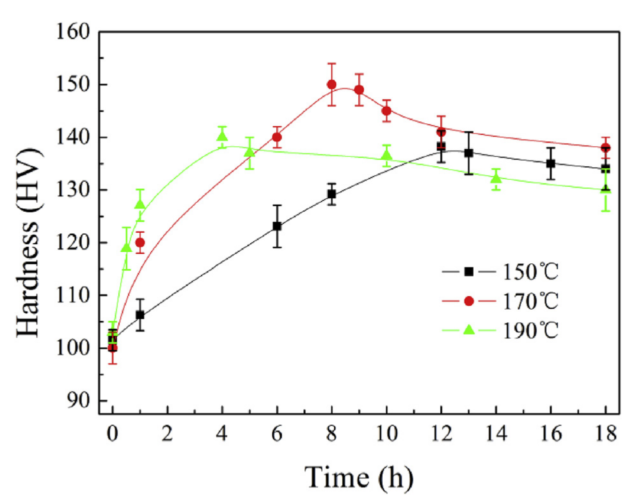

Fig. 1. Hardness vs. aging time at 150 °C, 170 °C, 190 °C of Be/6061Al composite.