Materials Characterization 96 (2014) 84–92

Contents lists available at ScienceDirect

Materials Characterization

journal homepage: www.elsevier.com/locate/matchar

Experimental and theoretical investigation on the compressive behavior of aluminum borate whisker reinforced 2024Al composites

Cheng Yang, Yingying Zong *, Zhenzhu Zheng, Debin Shan *

National Key Laboratory for Precision Hot Processing of Metals, Harbin Institute of Technology, Harbin 150001, China
School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

ARTICLE INFO

Article history:
Received 12 May 2014
Received in revised form 17 July 2014
Accepted 24 July 2014
Available online 25 July 2014

Keywords:
Metal matrix composites (MMCs)
Compressive deformation
Microstructures
Mechanical properties
Fracture
Hot workability

ABSTRACT

The compressive behavior of $Al_{18}B_4O_{33}$w/2024Al composites fabricated by squeeze casting was investigated under low and elevated temperature. Microstructure shows that the compression exerts a significant effect on whisker fracture and rotation. The theory of synergistic effects caused by different strengthening mechanisms is used to predict the yield strength. Experiments show that compressive yield strength of composites improves by 47% compared with those of 2024Al at 623 K and agrees relatively well theoretical value. The compressive deformation depends on matrix mainly at lower temperature and the main failure mode is shear fracture. Additionally, fracture mechanisms are investigated further through fracture surface analysis. During hot compression, the predominated softening mechanisms also include dynamic recrystallization and strain softening except for dynamic recovery, which corresponds well with the shape of flow curves, microstructural observation and change of activation energy. Lastly, the optimum process parameters are determined to be about 0.1 s^{-1} and 723 K based on Dynamic Material Model and validated by microstructure evolution. Experiments show that the strain rate has a mixed effect on whisker fracture.

1. Introduction

Metal matrix composites (MMCs) have aroused enormous concern during the past several decades, and aluminum matrix composites are regarded as promising materials because of the high specific modulus, high specific strength, excellent dimensional stability and good wear resistance [1–6]. Therefore, they have been considered to be applied in many fields, such as automotive and aerospace.

Aluminum borate whiskers ($Al_{18}B_4O_{33}$w) are regarded as a potential kind of whiskers to reinforce aluminum matrix with the advantages of excellent mechanical qualities and low cost in comparison with others, which can broaden the application in industry further [6–9]. As the performance of the composites depends on the aluminum matrix to a great extent, 2024Al alloy is widely considered to the promising matrix material because of its high strength, age hardenability and good workability [10,11]. Due to the existence of magnesium and copper in the 2024Al alloy, the interfacial reaction products [12,13] and intermetallics [14,15] can be formed in $Al_{18}B_4O_{33}$w/2024Al comparing to $Al_{18}B_4O_{33}$w/pure Al, which will have an influence on the mechanical properties.

Generally, the strengthening mechanisms of aluminum matrix composites can be investigated by different models due to the addition of the reinforcement [16,17]. The improvement of composites can be considered in perspective of the effective load transfer, enhanced dislocations triggered by thermal and geometrical mismatch, Orowan strengthening and so on [18–20]. However, the strength improves at the cost of reduction in plasticity. Fortunately, they show preferable plasticity when formed at elevated temperature [21]. In view of this, series of hot forming methods have been adopted, such as hot extrusion, hot rolling, hot compression and isothermal forging [6,22–27]. Factually, many defects still exist after hot forming, such as surface cracking and whisker fracture. Considering the widespread application in different fields, the workability analysis of aluminum matrix composites is indispensable. Since the forming quality is associated with the many parameters, researchers have conducted the experimental evaluation in conjunction with finite element methods [22]. Especially, as for hot compression, the processing map and kinetic analysis are effective ways to optimize the processing parameters to guarantee the service performance of composites [26,27].

Recently, some tests concerning the tensile behavior and thermal stability of $Al_{18}B_4O_{33}$w/2024Al with different coatings have been studied [28,29], and some researchers have demonstrated that the laser surface treatment can be adopted to improve corrosion properties of the composites [14]. However, researches related to compressive behavior of $Al_{18}B_4O_{33}$w/2024Al which is vital to explore the mechanical properties, fracture behavior, softening mechanism and suitable process parameters during hot compression have not been analyzed in detail.

In the present work, the compressive behavior of $Al_{18}B_4O_{33}$w/2024Al under low and elevated temperature was investigated, and

* Corresponding authors at: P.O. Box 435, No. 92 West Dazhi Street, Harbin 150001, China.
E-mail addresses: hagongda@hit.edu.cn (Y. Zong), d.b.shan@gmail.com (D. Shan).

http://dx.doi.org/10.1016/j.matchar.2014.07.024
1044-5803/

compared with the 2024Al alloy. The strengthening mechanism and surface fracture analysis were analyzed correspondingly. Particularly, the softening mechanisms of composites during hot compression were studied, the hot workability of composites was analyzed through kinetic analysis and processing map based on Dynamic Material Model in combination with microstructure evolution additionally.

2. Experimental

$Al_{18}B_4O_{33}$w whiskers with the length of 30–100 μm and diameter of 0.5–2.5 μm were used to reinforce 2024Al alloy by the squeeze casting technique. The volume fraction (V_f) of whiskers was 20%. The whiskers were distributed uniformly and oriented randomly in the 2024Al alloy. As for the matrix, the main chemical composition of 2024Al alloy except Al was 4.79% Cu, 1.49% Mg, 0.611% Mn, and 0.245% Fe. In the process of the squeeze casting, the preheating temperature of mold was 773 K and the matrix alloy was poured at 1073 K. After fabrication, the composites are solution-heated at 763 K and quenched down to the room temperature.

The compressive experiments were performed on Gleeble-1500 thermal–mechanical simulator at room temperature, 473 K and elevated temperature (623 K to 773 K at 50 K intervals) with a strain rate range between 0.001 and 1 s^{-1} in a vacuum. The compressive specimens were 8 mm × 12 mm and compressive reduction is 60% for hot compression. Specimens were firstly heated for 3 min and then compressed. Graphite was used as lubricant to reduce the friction and the composites were quenched by water after compression.

The microstructure of the composites and fractographs during compression were observed by a Quanta 200FEG and Helios Nanolab600i scanning electron microscope with energy-dispersive spectroscopy (EDS). These graphs concerning microstructure evolution are taken from the section parallel to the direction of compression. The interface between whiskers and 2024Al and specific microstructure were investigated using a Tecnai G2 F30 transmission electron microscope with an accelerating voltage of 120 kV. Meanwhile, the samples for TEM observation were thinned by ion milling.

3. Results and Discussion

3.1. Microstructure of Composites

Fig. 1 shows the micrographs of as-cast $Al_{18}B_4O_{33}$w/2024Al and compressed composites. It is clear that the whiskers break seriously during the fabrication with regard to the original materials. Large amount of hard phase $CuAl_2$ can be also observed, as proved by energy-dispersive spectroscopy (EDS) analysis (Fig. 1a). Except for hard phase $CuAl_2$, a few reaction products $MgAl_2O_4$ can be found between 2024Al alloy and whiskers (Fig. 1b). It can be concluded that compression exerts a significant effect on whisker fracture and rotation according to Fig. 1c. Many microcracks can be found around the clusters of broken whisker. In addition, whisker fracture is more serious around $CuAl_2$.

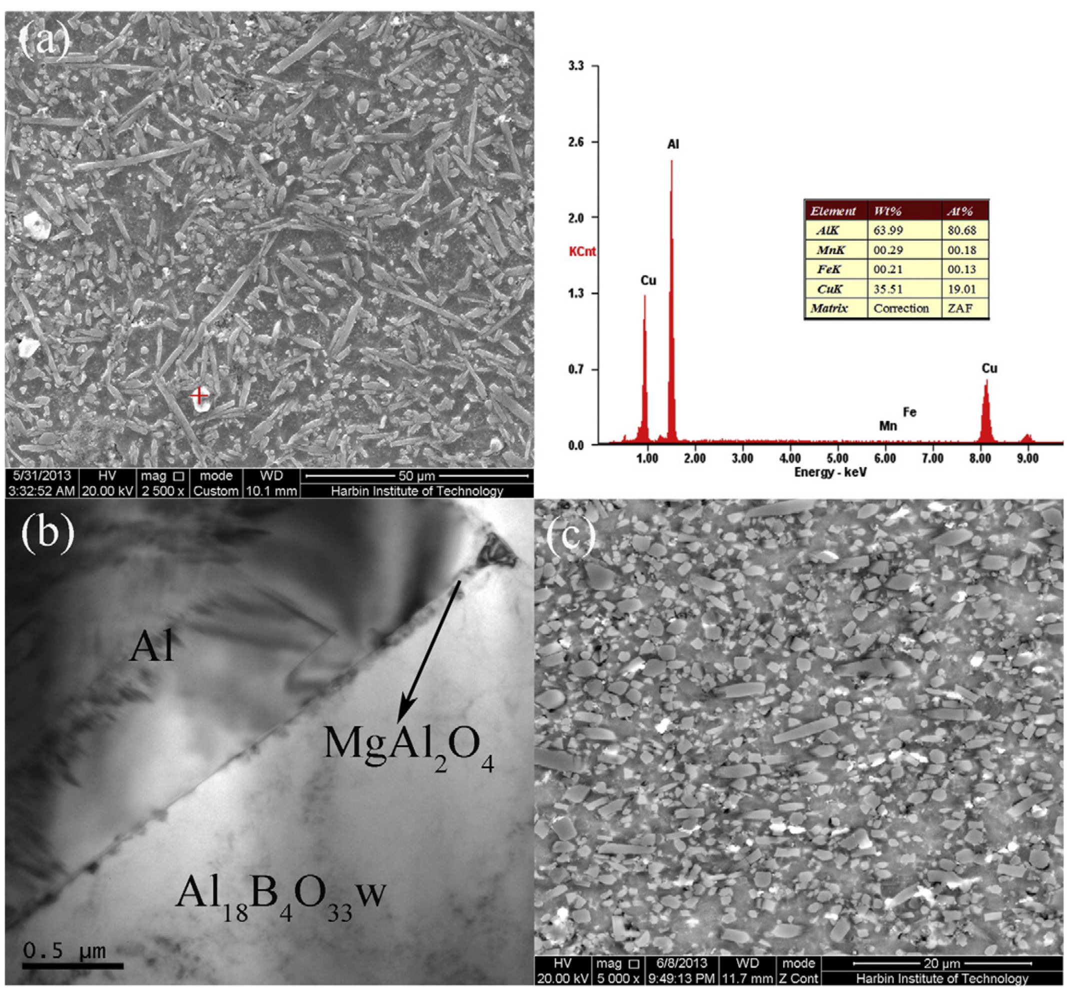

Fig. 1. Micrographs of (a) SEM, (b) TEM image of as-cast $Al_{18}B_4O_{33}$w/2024Al and (c) SEM image of compressed composites at 623 K and 0.1 s^{-1}.