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Evolutions of microstructure and mechanical properties for Mg-Al/AlN composites under hot extrusion

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ABSTRACT

Magnesium matrix composites reinforced with 5 wt% AlN particles were fabricated using the hot-pressing sintering followed by hot extrusion. The effects of hot extrusion on the microstructure and mechanical properties were investigated and the strengthening mechanisms of the hot-extruded Mg-Al/AlN composites were presented. The results showed the matrix grain was significantly refined and the uniformity of AlN particles distribution was effectively improved. However, the reinforcement particles were still mainly distributed along the grain boundary after hot extrusion. The remarkable improvement of mechanical properties was primarily attributed to the decreased grain size, improved dispersion of AlN particles and increased dislocation density. The fracture mode changed from layer cracking to mixed fracture with cleaved facets, dimples and fractured particles for the composites under hot extrusion.

1. Introduction

The light weight metals and composites have seen rapid developments in the research trend in recent years. Especially, the continuing research in automotive and aerospace industries largely targets on building light weight energy efficient vehicles in order to reduce the fuel consumption and the greenhouse gas emission [1–3]. It was reported that these materials are used in transportation vehicles, for example in an aircraft, reducing density is several times more efficient in reducing structural weight than increases in strength, damage and durability tolerance assessment, or the modulus of elasticity [4]. Among all structural material, magnesium alloys as the lightest have great potential to be used in aerospace and automobile industries [5]. Increasing the volumes of magnesium are being used in automotive industry can satisfy the demands for fuel efficient and low emission vehicles [6].

However, widespread application of Mg metal is limited due to its low strength, poor ductility, low wear resistance and lack of sufficient corrosion resistance. In order to overcome these limitations, various reinforcements such as SiC [7], B_4C [8], TiB_2 [9] have been used to produce magnesium matrix composites. It was noted that the mechanical properties of the composites are significantly improved over those of the matrix alloy, but there is very little research on magnesium MMCs reinforced with AlN particles. However, AlN ceramic not only can enhance the modulus, strength, hardness and wear resistance of the Mg matrix, as SiC and B_4C do, but can also be used as an electronic functional material due to its low coefficient of thermal expansion and good thermal conductivity [10,11]. It will be meaningful to study the Mg matrix composites reinforced with AlN particles, which would build excellent mechanical as well as thermal properties combined with superior weight saving capability. Some studies showed that the addition of AlN particles, have improved mechanical properties, lowered coefficient of thermal expansion and enhanced dimensional stability of Mg matrix alloy [12,13]. Nevertheless, the mechanical properties in the reports can be further improved. It is well known that extrusion can effectively improve the microstructure and properties of materials. Various new Mg alloys have been extruded, including rare-earth (RE)-containing and RE-free alloys, and these alloys have revealed a wide range of mechanical properties [14]. Lee et. al [4] reported that using reciprocating extrusion can simply and cost-effectively refine and homogenize the microstructure of Mg-15Al-1Zn alloy. Du et al. [15] reported that the mechanical properties of Mg-4.50Zn-1.13Ca (wt%) alloys can be significantly enhanced by the application of hot extrusion. During hot deformation, the microstructure evolution of composites, including the evolution of reinforcements and matrix, significantly influences their mechanical properties [16]. However, no attempt is made so far to study the influences of hot extrusion on

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microstructure and mechanical properties of Mg-Al/AlN composites in detail.

In this study, magnesium matrix composites reinforced with AlN particles were fabricated using the hot-pressing sintering followed by hot extrusion. The effects of hot extrusion on the microstructure and mechanical properties of the Mg-Al/AlN composites were investigated. The grain refinement, strengthening role and failure behavior produced by hot extrusion were discussed and analyzed.

2. Experimental

Commercial powders of Mg (> 99% purity, 75 μm, Kemio Chemical Reagents Co., Ltd., China), Al (> 99% purity, 10 μm, Titd Metal Materials Co., Ltd., China) and AlN (> 99% purity, 1–3 μm, Eno High-Tech Material Development Co., Ltd., China) were selected as the raw materials in this study. Powder mixtures with designed composition of 5 wt% AlN, and the balance are Mg and Al (the mass ratio of Mg to Al is about 91:9 as the composition of AZ91). The powder mixture together with agate balls, to maintain a ball-to-powder weight ratio of 6:1, was loaded into 500 ml nylon vial under argon atmosphere. About 2 wt% of stearic acid (purity: 99%, Tianjin Fuchen Chemical Reagents Factory, China) was used as a process control agent to minimize agglomeration of powder particles to each other and to the walls of the container and the grinding balls. A GLM roller mill (Xiangtan city instruments Co., Ltd., China) was used for mechanical milling at 70–100 r/min for over 24 h.

The milled powders were hot-pressing sintered at 590 °C for 1 h under argon atmosphere using 50 mm diameter dies. The sintered billets were then extruded at 330 °C to produce a bar with a diameter of 12 mm, and the extrusion ratio was about 17.36.

The microstructure of the specimens were observed using an optical microscope (OM, Leica DMI5000M) and a scanning electron microscope (SEM, VEGAI XMUINCA) equipped with energy dispersive X-ray spectrometry (EDS) system. Detailed structure was examined by transmission electron microscopy (TEM, JEM-200CX). The TEM samples were prepared by conventional procedures, which consist of mechanical polished to a thickness of around 40 μm, followed by ion-milled using a precision ion polishing system (Gatan 691) with the two ion guns. Grain sizes of as-received specimens were measured using optical microscope and the Image Pro-Plus Software. Bulk densities for all materials were measured using the Archimedes method, with absolute ethyl alcohol as the immersion media. Nanoindentation was performed using a nanoindenter (Hysitron TI 950, Minneapolis, MN, USA) equipped with a Berkovich diamond three-sided pyramid probe. A load-depth curve was obtained with a peak load of 8 mN from each indentation, and then reduced modulus (GPa) and hardness (GPa) were computed using Hysitron TriboScan software. The extruded rod was machined into cylindrical tensile specimens with a gauge diameter of 5 mm and a gauge length of 25 mm in accordance with ASTM E8M-04 standard. Four tensile specimens from different parts of the extruded rod were performed at room temperature. In addition, sheet tensile specimens were prepared for the hot-pressed billets to obtain tensile strength before extrusion, as shown in Fig. 1. The uniaxial tensile test was conducted at room temperature by using a material testing machine (Instron 1195), at the crosshead speed of 0.5 mm/min.

3. Results

3.1. Microstructure

The microstructures of Mg-Al/AlN composites before and after hot extrusion are shown in Fig. 2. Fig. 2a and b shows the microstructures of composite which are perpendicular to the hot-pressing and extrusion direction respectively, it is clear to see that the average grain size of the composite was much smaller after hot extrusion. The grain sizes of the Mg-Al/AlN composites before and after extrusion are shown in Table 1. It can be observed that the grain size was dramatically reduced after hot extrusion, which changed from 64.6 to 20.7 μm. The microstructure after hot extrusion is similar with the tri-modal composite reported in Al matrix composites [17], which consist of three phases: coarse-grained matrix, ultrafine-grained matrix and ceramic reinforcement. In addition, it can be observed that the reinforcement particles were mainly distributed along the grain boundary even though processed by hot extrusion. However, this phenomenon is more serious for the hot-pressing sintered specimen, due to some particles entered into grain interiors after hot extrusion.

Fig. 2c and d shows the longitudinal microstructures of composite which are parallel to the hot-pressing and extrusion direction respectively. It is obvious that the matrix grain was elongated and narrowed obviously along the extrusion direction after hot extrusion. Meanwhile, AlN particles were aligned in the longitudinal direction together with the $Mg_{17}Al_{12}$ phase, due to plastic flow of the matrix metal. Fig. 2e and f shows the distribution of AlN particles in high magnification, it can be observed that the particle aggregation in the matrix was obviously improved after hot extrusion. It is obvious that the matrix grain was not only significantly refined by hot extrusion, but also the uniformity of

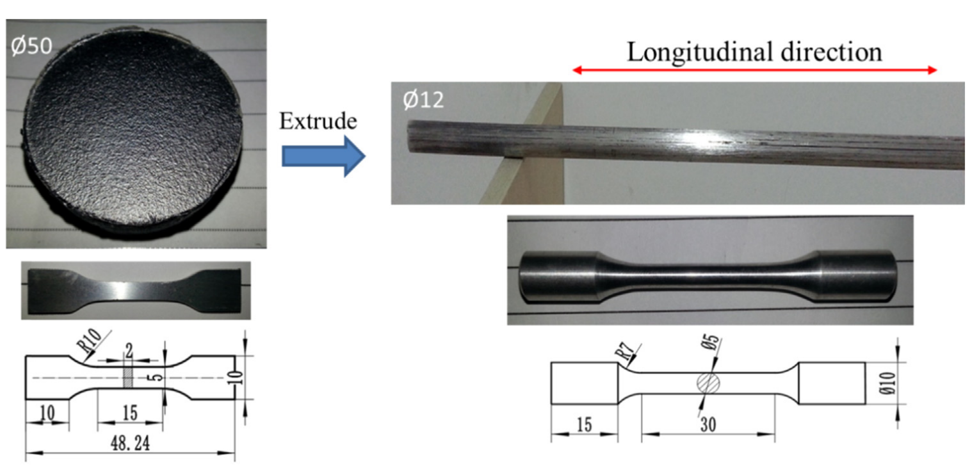

Fig. 1. Macroscopic morphologies and schematics of tensile specimens for the Mg-Al/AlN composites before and after hot extrusion.