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Compressive mechanical behavior of Al/Mg composite rods with different types of Al sleeve

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In the present study, mechanical behavior of two types of Al/Mg composite rods, Mg AZ31 core/soft Al 1100 sleeve and Mg AZ31 core/hard Al 7050 sleeve, under compression along the extrusion direction (ED) was systematically studied, with a great emphasis on the effect of different Al sleeves and Al fractions. The rule of mixtures for flow curve was also addressed. Our results show that the strength and fraction of Al sleeve greatly affect the shape of flow curves of Al/Mg rods. A plateau shape that often exists in flow curve of compression along the ED of a monolithic Mg extruded rod also appears in that of the Al/Mg rods. This plateau completely disappears with the fraction of Al 7050 up to 78.7%, but is still visible with Al 1100 86%. A fluctuation exists in the flow curves of composite with the soft Al 1100 sleeve, but is absent in those with the hard Al 7050 one. Different types of Al sleeve hardly affect the $\{10\bar{1}2\}$ twinning fraction in Mg core during ED compression. Compared to the soft Al 1100 sleeve, a hard 7050 one contributes to a homogeneous deformation of the whole composite and, hence, reduces the propensity for cracking at Al/Mg interface. The measured yield strengths of Al/Mg rods slightly deviate from the predicted ones by the rule of mixtures (about 4–36 MPa), while the rule of mixtures for the compressive flow curves does not work. It is found for the first time that the quite different strain hardening behaviors between the Mg core and the Al sleeve result in the large deviation of the experimental curves from the predicted ones.

1. Introduction

Hybrid metal composites are effective to improve mechanical behaviors including strength, plasticity, impact performance, abrasion resistance [1–4]. Al/Mg composites have provoked much interest in the fields of automobiles and aerospace owing to a combination of low density and desirable mechanical properties. Co-extrusion has become an effective and mass-production way for the production of metal composite rods for a long time. Generally, the volume fraction and architecture of each constituent can be precisely controlled during co-extrusion. During co-extrusion of a hybrid metal billet, a strong friction shear and an obvious adiabatic heating exist at interface between the core and sleeve, which might pose a great influence on microstructure and texture of the final products [5]. Recently, some publications have reported the fabrication of Al/Mg bimetal rods by co-extrusion, for example, pure Mg sleeve/pure Al core [6–10], Mg AZ31 sleeve/pure Al core [11], Mg AZ31 sleeve/Al 5052 core [11], Mg AZ31 sleeve/Al 7050 core [12], pure Al sleeve/pure Mg core [13], pure Al sleeve/Mg AZ80 core [2] and Al 6063 sleeve/Mg AZ31 core [14].

For composite rods like Al/Cu or Al/Fe, both constituents deform by dislocation slip during tension or compression along the extrusion direction (ED). With regard to a Al/Mg rod, tension along the ED also favors slip deformation in both Al and Mg. However, it is well established that compression along the ED of an extruded Mg rod is usually a $\{10\bar{1}2\}$ twinning predominant deformation [15,16]. Therefore, the ED compression of Al/Mg rods will simultaneously start $\{10\bar{1}2\}$ twinning in Mg and slip in Al. Consequently, the compressive deformation behavior of Al/Mg rods is quite different from that of rods Al/Cu [17–20] or Al/Al [21,22]. In recent years, several publications have addressed the compressive mechanical behavior of Al/Mg rods [7,10,12,13]. For a $\{10\bar{1}2\}$ twinning predominant deformation in Mg alloy, a plateau shape often exists in the flow curve [23]. This plateau is also observed to appear during ED compression of Al/Mg rods [7,10,12]. However, the Al fractions in those Al/Mg rods are often less than 20% and the knowledge

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regarding mechanical behavior of those Al/Mg rods with a higher Al fraction remains largely vague. Different types of Al alloy were used to fabricate Al/Mg rods, e.g. pure Al or Al 1100 with a much lower strength than Mg constituent (Mg AZ31 or AZ80) or Al 7050 with a much higher strength [2,11,12]. Up to now, there is not a systematical study addressing how the Al fraction and Al/Mg strength ratio affect mechanical behavior of Al/Mg rods.

For hybrid metal composites, the relationship between mechanical behavior of composite and its constituents is an important issue. A deep understanding about this relationship contributes to predicting mechanical performance of composites. Many studies have reported that the rule of mixtures (ROM) worked for the strength, flow curve or the overall hardening behavior of bimetals [6,7,24–30]. However, in those studies, both the flow curves of the two components corresponded to a slip predominant deformation and adopted a similar concave-down shape. In contrast, compression along the ED of Mg rod is often accompanied by a $\{10\bar{1}2\}$ twinning predominant deformation and a sigmoidal shaped flow curve. A clear picture of whether the ROM works or not during compressive deformation of Al/Mg rods is still lacking.

In the present study, two types of Al/Mg composite rods, Mg AZ31 core/soft Al 1100 sleeve and Mg AZ31 core/hard Al 7050 sleeve, were fabricated by co-extrusion. The deformation and mechanical behavior under compression along the ED of those two types of composite rod were systematically studied, with a great emphasis on the effect of different Al sleeves and Al fractions. The ROM for flow curve was also addressed by an accurate measurement of the mechanical properties of each component cut directly from the Al/Mg composite. The present study provides new insights into deformation and mechanical behavior of bimetal composites.

2. Experiments and methods

2.1. Extrusion and mechanical tests

As-cast Mg AZ31, Al 1100 and 7050 in the homogenized condition were used to fabricate the Al/Mg rods. As seen in Fig. 1a, two types of Al/Mg rod (the designated 7050/AZ31 and 1100/AZ31) were fabricated with Al alloy as the sleeve and Mg alloy as the core. Al 7050 and 1100 billets were machined into hollow cylinders with an outer diameter 80 mm and an inner 30 mm. Mg AZ31 cylinders with a diameter of 30 mm were cut, polished and filled into the Al hollow cylinders. Those two types of Al/Mg bimetal billet were kept in furnace at 470 °C for 2 h and immediately extruded at 450 °C using an extrusion ratio 25:1 and an extrusion rate of 0.75 m/min. The extruded 7050/AZ31 rod was immediately quenched in warm water (60 °C) after exiting the die followed by aging at 120 °C for 8 h. The final extruded rods have a diameter of 16 mm and a Mg core of about 6 mm in diameter. In order to get a fully recrystallized and equiaxed grains, the extruded rods were annealed at 400 °C for 63 h. The annealed 7050/AZ31 rod was subsequently aged at 150 °C for 9 h to suppress the aging in Al 7050 at room temperature. To study the ROM for flow curve, an Al/Al rod with Al 7050 as the core and Al 6082 as the sleeve was fabricated by extrusion of an Al 6082/Al 7050 bimetal billet at 450 °C using an extrusion ratio 25:1 and an extrusion rate 0.75 m/min. The as-extruded Al/Al rod was aged at 175 °C for 11 h.

To prepare the Al/Mg samples with different Al fractions (Fig. 1b), the as-extruded 7050/AZ31 and 1100/AZ31 rods were machined into six types of rod with different diameters (8 mm, 9 mm, 10 mm, 11 mm, 13 mm and 16 mm). As the diameter of Mg cores in the six types of rod are the same (6 mm), the Al fraction varies from 43.7% to 86%. The designations of samples are given in Table 1. To measure mechanical properties of the Al sleeve and Mg core, cylindrical specimens containing only Al component or Mg component were cut directly from the Al/Mg rods for mechanical tests (Fig. 1b). Compression tests along the ED at room temperature were performed on a Shimadzu mechanical testing system using a strain rate of 10^{-3} s^{-1}. Each mechanical test was repeated three times. The load-displacement data from the load frame were corrected for machine compliance and then used to calculate true stress and true strain.

2.2. Examination of microstructure and texture

Electron backscattered diffraction (EBSD) measurements using a step size of 1 μm were performed on a FEI Nova 400 SEM equipped with a HKL Channel 5 system. The specimens for EBSD mapping were carefully ground with a series of SiC sand papers followed by electrochemical polishing (AC2 electrolyte for Mg core and perchloric acid solution for Al sleeve (1 ml perchloric acid + 9 ml ethanol)) at 20 V. Twinning deformation in Mg core during compression along the ED was also studied by EBSD on a cross section in the middle of cylinder. To acquire a statistical and reproducible results about the texture and twin fraction, two EBSD maps of 400 μm × 400 μm were recorded. The step size for EBSD

Table 1
The designation of different Al/Mg samples.

Sample (sleeve/core)	Al fraction (%)	Sample (sleeve/core)	Al fraction (%)
7050/AZ31-1	43.7	1100/AZ31-1	43.7
7050/AZ31-2	55.6	1100/AZ31-2	55.6
7050/AZ31-3	64.0	1100/AZ31-3	64.0
7050/AZ31-4	70.3	1100/AZ31-4	70.3
7050/AZ31-5	78.7	1100/AZ31-5	78.7
7050/AZ31-6	86.0	1100/AZ31-6	86.0
7050/AZ31-7050	100	1100/AZ31-1100	100
7050/AZ31-AZ31	0	1100/AZ31-AZ31	0

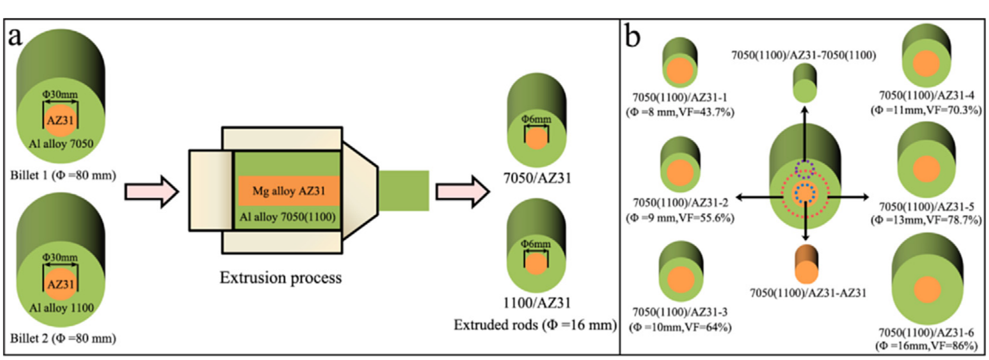

Fig. 1. A schematic diagram showing (a) the fabrication of Al/Mg bimetal rods by extrusion and (b) preparation of specimens for compression tests.