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Constitutive behavior of a SIMA processed magnesium alloy by employing repetitive upsetting-extrusion (RUE)

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ABSTRACT

Thixotropic compression tests were carried out on a repetitive upsetting-extrusion (RUE) processed AZ91D magnesium alloy at temperatures ranging from 500 °C to 550 °C by using a Gleeble-1500 thermal-mechanical simulator. Semi-solid stress-strain data were obtained. A modified constitutive model was established to describe the thixotropic behavior of the RUE strained alloys. The results revealed that three stages of elastic-like deformation, strain hardening deformation and rheological viscoplastic deformation were involved in the thixoforming process. Furthermore, the compressed microstructures in semi-solid state were investigated with referring to microstructure observation. Dominant deformation mechanisms during the thixotropic compression were considered as the slipping or rotating mechanism of the solid particles along the liquid films, the slipping mechanism between the solid particles, the plastic deformation mechanism of the solid particles and the DRX behavior of the solid particles, whose function varied with the change of temperature and strain rate.

1. Introduction

Magnesium alloys, as the lightest structural alloys, have been widely applied in many fields, especially in aviation, spaceflight, traffic, war industry and so on [1–3]. However, their extensive applications are restricted in many industry fields owing to their poor plastic workability [4]. Therefore, the semi-solid forming process (SSF) of magnesium alloys has been greatly concerned in recent years on account of its outstanding advantages of small applied load, low energy consumption as well as excellent mechanical properties of products. Numerous studies have suggested that the SSF technique is expected to be an effective method to solve the bottlenecks restricting the application of magnesium alloys [5,6]. Microstructure of the semi-solid metals is composed of spherical or nearly spherical solid grains and liquid composition. Thixoforming with the semi-solid metals as raw material has the characteristics of low shear stress and good filling performance. In view of optimizing the process variables and preparing thixoformed products with high mechanical performance, it is of great significance to understand the thixotropic behavior of the semi-solid alloys. Most of the literature and researches have focused on the preparation of semi-solid billets, mechanical properties of products and semi-solid forming equipment with respect to the semi-solid forming of magnesium alloys [7,8,24,26]. Nevertheless, the constitutive behavior and microstructural evolution of magnesium alloys during the semi-solid forming process, especially for the highly strained magnesium alloys as the initial billet, are still rarely reported.

The present work was conducted to aim at revealing the semi-solid compression behavior of a strain induced melt activation (SIMA) processed AZ91D magnesium alloy by employing a novel repetitive upsetting-extrusion (RUE) intense plastic straining process. Thixotropic compression tests of the SIMA treated alloy were performed. Stress-strain data were provided and the thixotropic performance was studied during the semi-solid compression. The effect of reheating temperature and strain rate on the thixotropic behavior and microstructural development during the semi-solid compression process were clarified. The morphology variations of solid grains and the flow pattern of liquid composition under various conditions were revealed with referring to microstructure observation. Furthermore, the deformation mechanisms were discussed in detail for the RUE-based SIMA processed alloys during the semi-solid compression process.

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2. Materials and experimental procedure

2.1. Preparation of semi-solid billet

The as-cast AZ91D magnesium alloy was used as the experimental material in the present investigation, which has a nominal composition of Mg-8.83Al-0.578Zn- 0.157Mn-0.1Si-0.005Fe-0.005Cu-0.002Ni (all in wt.%). The primary microstructure and XRD (X-ray diffraction) pattern of the as-cast alloy are illustrated in Fig. 1(a) and (b), respectively. It can be seen that the as-cast structure consists of coarse dendritic α-Mg grains and interlaced networks of β-$Mg_{17}Al_{12}$ phases. The average grain size is determined to be about ~180 μm. Meanwhile, a few cracks and pores are exhibited in the as-cast structure (Fig. 1(a)).

The semi-solid billets used for thixotropic compression tests were prepared by the SIMA method by adopting a RUE severe plastic deformation as the predeformation route. The RUE process is a kind of innovated SPD approach for inducing large accumulated strain to materials, which is firstly presented by Hu et al. [28] on basis of the idea of bulk mechanical alloying. It is revealed from their investigations that severely deformed alloys remain initial height and diameter after multi-cycle RUE process. In addition, the RUE process also has the advantages of simple operation, low applied load and significant microstructural refinement. The process schematic drawing is given in Fig. 2. It is illustrated that the RUE process consists of successive cycles of conventional upsetting operation followed by direct extrusion operation. The whole process is carried out in a closed die, which facilitates better shape control of severely strained billet. In the present work, the RUE process tests were conducted on a 100t hydraulic press. An oil-based graphite lubricant was used to reduce the friction between the die parts and the billet. Initial specimens with a dimension of Ø14 mm × 40 mm were machined from the as-cast alloy. Firstly, the as-cast specimens were subjected to the RUE process at 340 °C for three cycles with a ram speed of 6 mm/s. The accumulative plastic strain after three cycles was 3.75 approximately. Then the RUE strained alloys were isothermally treated at 580 °C for a soaking time of 15 min. An immediate water quenching was conducted for the isothermally treated alloys to examine the semi-solid microstructure before thixotropic compression tests. Finally, cylindrical specimens with a dimension of 6 mm in diameter and 9 mm in height were cut from the SIMA processed alloys.

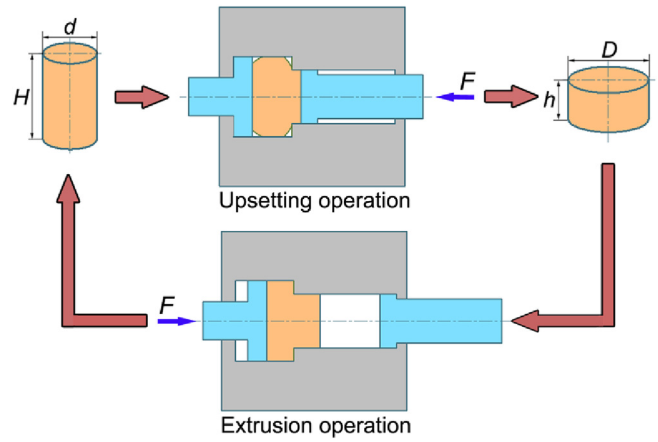

Fig. 2. Schematic of the RUE process. (a) upsetting operation, (b) finish of upsetting operation, (c) extrusion operation, (d) finish of extrusion operation.

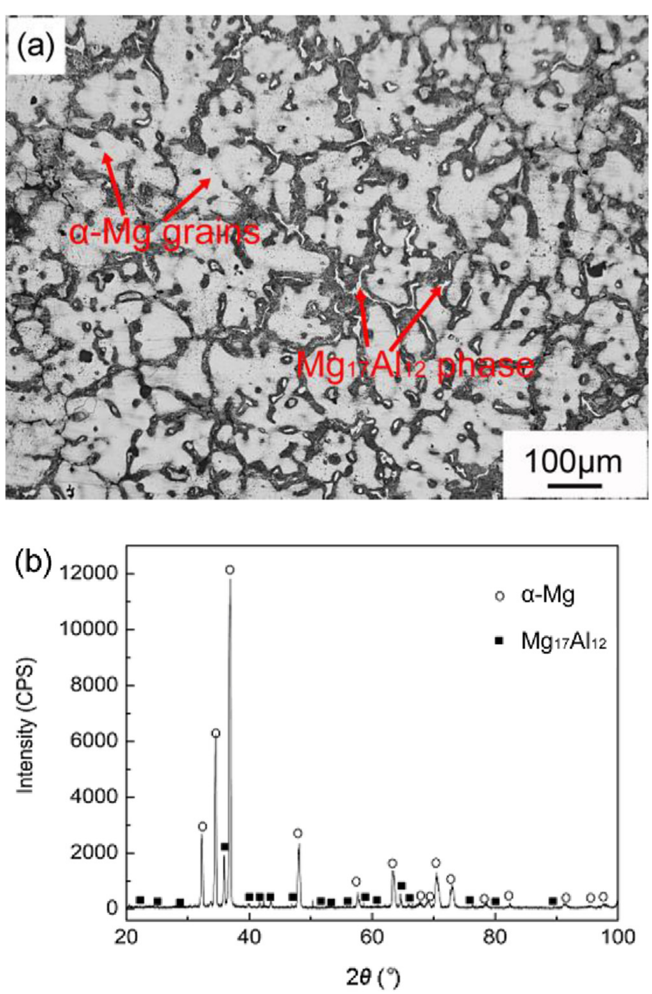

Fig. 1. (a) Primary microstructure and (b) XRD pattern of the as-cast AZ91D magnesium alloy.

2.2. Thixotropic compression tests

The thixotropic compression tests were conducted on a Gleeble-1500 thermal mechanical simulator. During the tests, graphite gaskets were used to reduce the friction between the end and the press head of the test machine. For uniform heating of the samples, different heating rates were adopted during the heating process of the semi-solid compression tests, as shown in Fig. 3. Before the thixotropic compression, the sample was firstly heated to a

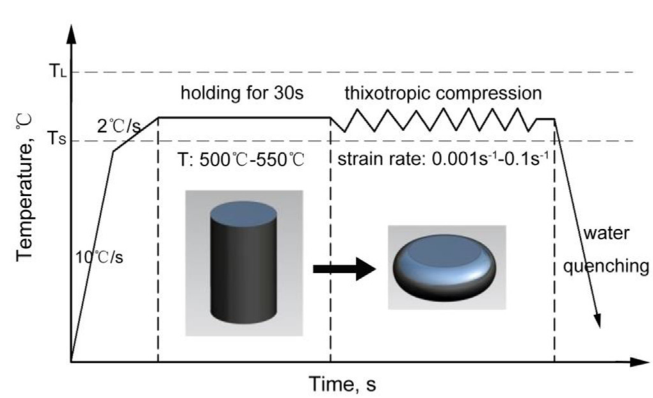

Fig. 3. Schematic of the thixotropic compression.