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Microstructure evolution of a SIMA processed AZ91D magnesium alloy based on repetitive upsetting-extrusion (RUE) process

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A B S T R A C T

Repetitive upsetting-extrusion (RUE) was introduced into the strain induced melt activation (SIMA) process. The semi-solid feedstock of AZ91D magnesium alloy with superior thixotropic features was successfully prepared by the modified SIMA process. Prior to partial remelting, the process involving the application of RUE pre-deformation to as-cast alloy was conducted. Consequently, a severely strained structure consisting of fine α-Mg grains and highly fragmented β-$Mg_{17}Al_{12}$ particles was obtained. During the subsequent isothermal treatment between the solidus and the liquidus, the microstructure evolution of the RUE processed alloys subjected to various deformation cycles and temperatures was investigated at the temperature range of 550–580 °C for various durations. The results indicated that the RUE-based SIMA process was a valid route for preparing high-quality thixotropic materials, and the isothermally treated microstructure consisted of fine solid globules surrounded by uniform liquid films. The microstructure evolution model for the modified SIMA process was proposed with reference to the micrograph examination. And the mechanisms responsible for the spheroidization and coarsening of the globular structure were discussed in detail. Further study on effective parameters clarified that the thixotropic features of semi-solid slurry were affected by the parameters of RUE process as well as the isothermal treatment process. And the desirable globular structure, featured by fine, homogeneous and well globularized solid grains and continuous liquid films, was obtained by three-cycle RUE process at 285 °C followed by isothermal treatment at 560 °C for 15 min.

1. Introduction

The demand of magnesium alloys for applications in various industry fields has been increased rapidly due to their excellent comprehensive performances, such as low density, high specific strength and stiffness, super damping and thermal conduction, etc. [1–3]. However, magnesium alloys have poor plastic forming ability because of a hexagonal close-packed (HCP) crystal structure [4]. Therefore, the magnesium alloys are principally produced by traditional casting process. The inevitable internal metallurgical defects generated during casting, such as microstructural coarseness, microsegregation, porosity and shrinkage cavity, always seriously affect the mechanical properties of components. This restricts the application of magnesium alloys. The advent of semi-solid metal forming (SSF) provides an effective technical approach for manufacturing magnesium-alloy components with complex structure and high mechanical properties. Compared with traditional casting and forging approaches, the SSF process has some potential benefits for the production of magnesium alloys [5–7]: low production cost, high efficiency, low gas porosity, production of thin-walled and complex structural components, near-net shaped processing, high-performance components production, low processing temperature, namely anti-oxidation and anti-combustion, long die lifespan, and so on.

The key issue of SSF is the production of semi-solid slurry (for rheological forming) or feedstock (for thixoforming) with uniform and fine globular structure [8,9]. In this regard, a lot of researches have been conducted. It was reported from the previous literatures that the semi-solid slurry of an A357 aluminum alloy and a nano-sized SiC/7075 aluminum matrix composite was successfully prepared by annulus electromagnetic stirring (AEMS) [10] and ultrasonic-assisted semisolid stirring (UASS) [11], respectively. However, these liquid metal routes are not suitable for the preparation of semi-solid feedstock for magnesium alloys due to their oxidation and burning at high temperatures. In contrast, the solid state route of strain-induced melt activation (SIMA), proposed by Young [12], has been proved to be a more effective process for the production of semi-solid magnesium alloys. SIMA process includes two chief routes of severe plastic deformation (SPD) and subsequent semi-solid isothermal treatment (SSIT) [13]. The former plays a critical role for controlling the thixoforming microstructure. Owing to the highly

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induced strain after SPD route, the matrix phase was refined significantly and the coarse second phases with lower-melting point in original microstructure were effectively crushed. This may hasten the evolution of globular structure during SSIT route, resulting in the high quality semi-solid feedstock with more spherical and smaller solid grains. Conventional upsetting route and extrusion route have been introduced to SIMA process by Nayyeri and Khomamizadeh [14] and Xia [15], and the globular semi-solid structures of Mg–4Al alloys containing various rare earth elements and AZ91D magnesium alloy were obtained, respectively. But it can be speculated that blank size would change seriously when a higher induced strain was imposed, leading to a loss of industrial application. Recently, more researches have been focused on the SIMA approach by using equal channel angular extrusion (ECAE). ECAE was employed by Jiang et al. [16] as the pre-deformation process for AM60 magnesium alloy before remelting activation. The results showed that the microstructure of as-cast alloy was significantly refined after ECAE deformation and the semi-solid feedstock with very fine and spheroidal solid grains was prepared. Zhao et al. [17] also investigated microstructural evolution of an ECAE-formed ZK60-RE magnesium alloy in the semi-solid state. Ideal semi-solid state structure was produced by the combination of ECAE process and partial remelting. It was also found that solid grains were refined and liquid formation rate was enhanced more obviously as the numbers of ECAE passes increased. However, recent literature [18] indicated that non-uniform deformation behavior was observed during ECAE process. It was also discovered that deformation texture would generate and develop easily in case the deformation routes were not properly controlled [19–21]. This brought out the subsequent combination and growth of solid grains in partial remelting process, resulting in inhomogeneous and coarse semi-solid structure [22]. Moreover, the end faces of ECAE-formed blanks were not perpendicular to axis. Material removal at both ends of pre-deformed blanks was needed prior to partial remelting, leading to material waste and high production cost. Repetitive upsetting-extrusion (RUE) [23] was an effective SPD method for microstructure refinement and performance improvement in bulk materials. Hu and coworkers [24] have investigated grain refinement mechanisms for LY12 aluminum alloy during RUE process. They suggested that high accumulative induced strain was achieved easily by imposing desired RUE cycles. Uniform and fine structure was obtained. More importantly, the severely strained blanks remained geometric invariant after multiple RUE process cycles.

The current work was aimed to develop a modified SIMA approach by employing RUE process, and the validity for preparing thixotropic material was demonstrated by experimental investigation on an AZ91D magnesium alloy for the first time. Microstructure evolution of RUE formed alloy in solid state and partial remelting state was examined. The microstructure evolution model of the RUE-based SIMA process was proposed to explain the mechanisms responsible for the spheroidization and coarsening of the globular structure. Moreover, the effects of RUE process cycle and deformation temperature, isothermal temperature and holding time on the spheroidization and coarsening of semi-solid microstructure were investigated.

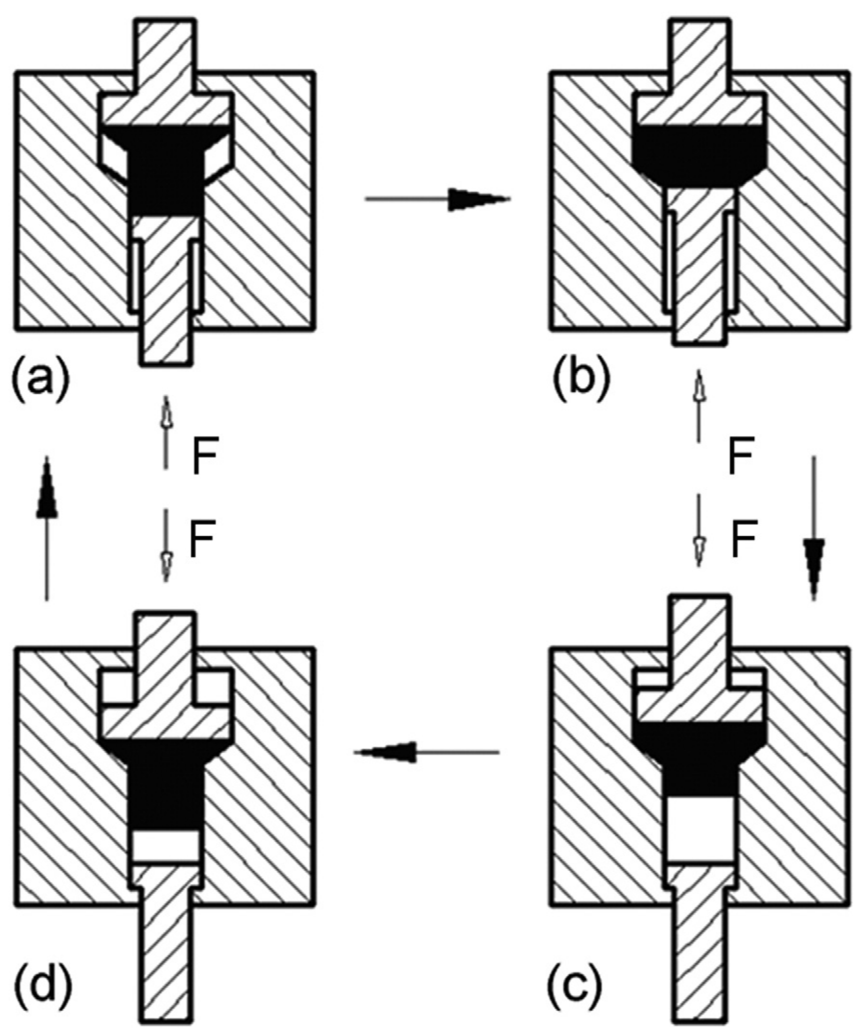

Fig. 1. Schematic illustration of repetitive upsetting-extrusion (RUE) process: (a) upsetting, (b) finish of upsetting, (c) extrusion and (d) finish of extrusion.