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ScienceDirect
JOURNAL OF RARE EARTHS
JOURNAL OF RARE EARTHS, Vol. 31, No. 3, Mar. 2013, P. 319
www.re-journal.com/en/

Grain coarsening in semi-solid state and tensile mechanical properties of thixoformed AZ91D-RE

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Received 29 November 2012; revised 17 January 2013

Abstract: For thixoforming to be possible, the microstructure of the starting material must be non-dendritic, which can be obtained by the strain induced melt activation (SIMA) route. Based on the SIMA route, as-cast AZ91D alloy with the addition of yttrium was deformed by cyclic closed-die forging (CCDF). Microstructure evolution of CCDF formed AZ91D-RE alloy during partial remelting were investigated. Furthermore, the mechanical properties of thixoformed AZ91D-RE magnesium alloy components were also studied. The results showed that prolonged holding time resulted in grain coarsening and the improvement in degree of spheroidization. The coarsening behaviour of solid grains in the semi-solid state obeyed Ostwald ripening mechanism. The coarsening rate constant of CCDF formed AZ91D-RE during partial remelting was 324 um3/s at 550 ºC. The value of yield strength, ultimate tensile strength and elongation to fracture of four-pass CCDF formed AZ91D-RE magnesium alloy were 214.9, 290.5 MPa and 14%, respectively. Then the four-pass CCDF formed alloys were used for thixoforming. After holding at 550 ºC for 5 min, the values of yield strength, ultimate tensile strength and elongation to fracture of thixoformed component were 189.6 MPa, 274.6 MPa and 12%, respectively. However, prolonged holding time led to remarkable decrease in mechanical properties of thixoformed components.

Keywords: magnesium alloy; microstructure; mechanical properties; thixoforming; partial remelting; rare earths

Magnesium alloys have characteristics of low density, high specific strength and excellent machinability, attracting more and more researchers' attention[1–3]. However, their poor mechanical properties make them impossible for wide applications in electronics, automotive and aerospace industries[4]. Recently, it has been reported that the addition of rare earths (RE) can improve the mechanical properties of magnesium alloys[5–7].

The semi-solid metal (SSM) processing offers an opportunity to produce magnesium alloy components. Compared with conventional casting and forging, the SSM processing shows several potential advantages, such as the reduction of porosity, less entrapped air and low forging force[8–10]. The process requires that alloys should be treated so that they possess a non-dendritic, spheroidal microstructure when they are reheated between the solidus and liquidus. There are several routes to achieve a non-dendritic microstructure, such as cooling slope (CS), semi-solid thermal transformation (SSTT), strain-induced melt activation (SIMA) and recrystallization and partial remelting (RAP)[11–13]. In the SIMA process, material which has worked at temperatures above the recrystallization temperature is then reheated to the semi-solid state. The RAP process is allied to the SIMA process. The main similarity between the SIMA process and the RAP process is that a critical level of strain must be introduced into the material through deformation. Clearly the difference between the SIMA & RAP processes is the deformation temperature, hot working as opposed to warm working respectively [14–16].

Several researchers[17–19] have reported on the microstructural evolution and mechanical properties of semi-solid processed magnesium alloys. Zhao et al.[17] firstly have reported that the application of cyclic closed-die forging (CCDF) as a SIMA route for AM60B magnesium alloy semi-solid processing. The results showed that the CCDF process improved the mechanical properties of AM60B alloy, especially after four-pass CCDF. Then the four-pass CCDF formed alloys were used for thixoforming and the good mechanical properties were obtained in the final thixoformed products. Chen et al.[18] innovated a new process to prepare semi-solid billets. In the new process, squeeze casting-solid extrusion followed by partial melting was proposed to obtain the semi-solid feedstock for thixoforging. The innovative process distinctly improved the quality of semi-solid billets and reduced the cost. The new process has been shown to produce ideal, fine SSM structures, in which completely globular

Foundation item: Project supported by Natural Science Foundation of Heilongjiang Province (ZD20081901, QC2012C006)

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DOI: 10.1016/S1002-0721(12)60279-8

primary phase particles were essentially free of entrapped liquid. Luo et al.[19] have reported that the effects of isothermal holding time on the semi-solid microstructures of ZK60 alloys prepared by the RAP process. They found that the coarsening behaviour of solid particles in the semi-solid state obeyed Ostwald ripening mechanism. The coarsening rate constant obtained was 556 $\mu m^3/s$ at 590 ºC.

In the conventional SIMA route, compression or extrusion was used to pre-deform magnesium alloys. Due to limited amount of plastic deformation, the microstructure treated by compression was very inhomogeneous, which resulted in bimodal structures in the semi-solid state. As for extrusion, the cross-section shape of billets was changed. To overcome disadvantages mentioned above, the CCDF process was introduced into a SIMA route for semi-solid forming in this work[20]. The principle of the CCDF process is represented schematically in Fig. 1. As shown in Fig. 1, W is the width of specimen and H is the height of specimen.

The aim of the present paper is to employ the CCDF process to pre-deform AZ91D-RE magnesium alloy in the SIMA route. The microstructural evolution of CCDF formed AZ91D-RE magnesium alloy after partial remelting was studied. Furthermore, the mechanical properties of thixoformed AZ91D-RE magnesium alloy were also investigated.

1 Experimental

In this work, the alloy used was an as-cast magnesium alloy with yttrium (Y) addition, AZ91D-RE (Mg-8.92%Al-1.18%Zn-0.09%Mn-1.5%Y), where the compositions were in wt.%. AZ91D alloy was melted in an electric resistance furnace protected by SF_6 and CO_2 gas (mixing ratio was 1:100) to avoid oxidation at 750 ºC. Then Y element in the form of Y-rich inter-alloy was added into the metal at 760 ºC for about 20 min to ensure that the Y was completely dissolved. After that the metal was poured into a steel die kept at room temperature. Billets with dimensions of 80 mm×80 mm×160 mm for CCDF

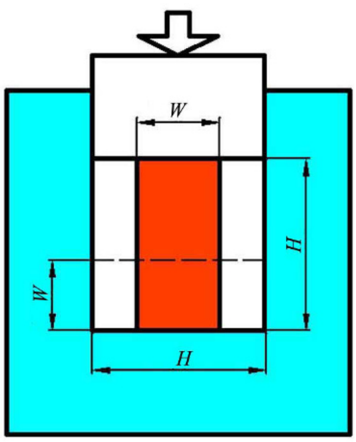

Fig. 1 Schematic of cyclic closed-die forging (CCDF)

were machined from the AZ91D-RE alloys. During CCDF, all of the AZ91D-RE billets were processed for four pass with a speed of 2 mm/s and each pass was imposed the equivalent strain (ε_e) of 0.8 on billets. Before CCDF, AZ91D-RE billets were preheated to 350 ºC for 45 min and the closed die was heated up to 350 ºC. And then AZ91D-RE billets were processed through the CCDF, AZ91D-RE billets were preheated to 350 ºC for 45 min and the CCDF die was heated up to 350 ºC. AZ91D-RE billets were processed through the CCDF die. Molybdenum disulphide (MoS_2) was used as a lubricant.

AZ91D-RE billets treated by CCDF were machined into cylindrical samples with sizes of Φ10 mm×12 mm for partial remelting experiments. The samples were heated in a vertical infrared tube furnace at 550 ºC under the protective atmosphere of flowing argon to prevent oxidation, isothermally held and quenched in water of 0 ºC as soon as removal from the furnace. To ensure accurate temperature measurement, a thermocouple was embedded in a small hole with sizes of Φ2 mm×5 mm.

Before thixoforming, the four-pass CCDF-formed AZ91D-RE billets were machined into some slugs with sizes of Φ70 mm×60 mm. The temperature of the slug was monitored by a K-type thermocouple, which was embedded in the slug. After the required temperature and holding time was reached, the thermocouple was removed from the slug. The temperature of slug was 550 ºC. Moreover, the temperature of die used for thixoforming was 350 ºC. The die used for thixoforming is shown in Fig. 2.

All of the metallographic specimens were etched with All of the metallographic specimens were etched with a solution of 10 ml water, 100 ml ethanol, 5 ml acetic acid

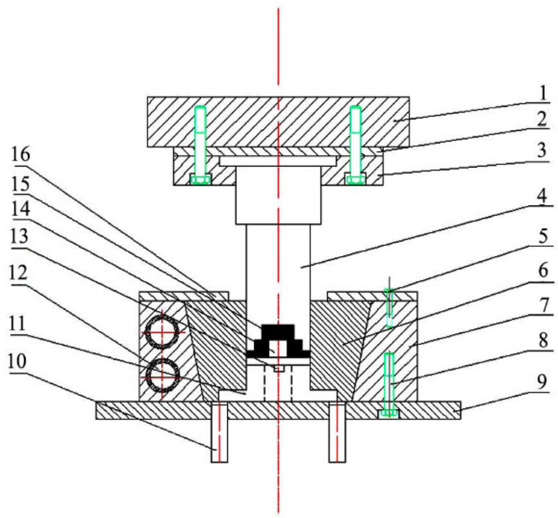

Fig. 2 Die used for thixoforming

1-Upper pattern plate; 2-Backing plate; 3-Mounting plate; 4-Upper punch; 5-Screw bolt; 6-Die sleeve; 7-External die sleeve; 8-Screw bolt; 9-Down pattern plate; 10-Ejector pin; 11-Die holder; 12-Resistance wire; 13-Tap hole; 14-Mould core; 15-Component; 16-Pressure back