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Development of the rheo-diecasting process for magnesium alloys

Z. Fan *

BCAST (Brunel Centre for Advanced Solidification Technology), Brunel University, Uxbridge, Middlesex UB8 3PH, UK

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Abstract

The rheo-diecasting (RDC) process is an innovative one-step semisolid processing technique for manufacturing near-net shape components of high integrity directly from liquid Mg-alloys. The process innovatively adapts the well-established high shear dispersive mixing action of the twin-screw mechanism to the task of in situ creation of semisolid metal (SSM) slurry with fine and spheroidal solid particles followed by direct shaping of the SSM slurry into a near-net shape component using the existing cold chamber high pressure diecasting (HPDC) process. In this paper, we present the RDC process, and the resulting microstructures and mechanical properties of various Mg-alloys. The experimental results show that the RDC samples have extremely low porosity (typically 0.1–0.3%), fine and uniform microstructure throughout entire casting, and consequently much improved strength and ductility, compared with those produced by the HPDC process and other semisolid processes. In addition, the RDC process is more tolerant to alloy composition in terms of processability.

Keywords: Rheocasting; Microstructure; Mechanical properties; Magnesium alloys

1. Introduction

Currently, nearly all the applications of Mg-alloys are provided by high pressure diecasting (HPDC), due to its high efficiency, high production volume and low production cost. However, HPDC components contain a substantial amount of porosity due to gas entrapment during die filling, and hot tearing during the solidification in the die cavity [1]. Such porosity not only deteriorates mechanical properties, but also denies the opportunity for property enhancement by subsequent heat treatment. Further growth in Mg applications will largely depend on the successful development of new processing technologies capable of producing high quality, low cost components [2].

One of the promising technologies capable of producing high integrity components is semisolid metal (SSM) processing [3,4]. Compared with conventional diecasting routes, SSM processing has a number of advantages, such as low porosity, heat treatability, consistency and soundness of mechanical properties, the ability to make complex component shapes and longer die life [3,4]. One of the most popular SSM processes currently used is thixoforming [5], in which non-dendritic alloys pre-processed by electromagnetic stirring [6] are reheated to the semisolid region prior to the component shaping by either casting (thixocasting) or forging (thixoforging). It is therefore a two-stage process. The high cost of pre-processed non-dendritic raw materials is by far the greatest obstacle to the development of the full potential of this approach [7]. Due to the lack of reliable and quality feedstock supply, thixoforming of Mg-alloys has been very scarce. So far, only thixomoulding [8] of thin-walled components has achieved some success in engineering applications. In recent years, to overcome the technical and economical difficulties faced by the thixo-processing route, the rheo-route of SSM processing has become popular for research and development [9]. This includes the new rheocasting (NRC) process developed by UBE [10], the SSR process developed by MIT [11] and the continuous rheo-conversion (CRP) process developed by WPI [12]. A common feature of rheo-processing techniques is that they all use molten alloy as a starting material, therefore eliminating the need for specially prepared feedstock materials.

In this paper, we report a new semisolid processing technique, the rheo-diecasting (RDC) process. Microstructure and mechanical properties of the RDC Mg-alloys will be presented and compared with those produced by other processes.

* Tel.: +44 1895 266406; fax: +44 1895 269758.
E-mail address: Zhongyun.Fan@brunel.ac.uk.

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2. The RDC process and experimental procedures

The RDC process, as schematically illustrated in Fig. 1, is an innovative one-step SSM processing technique for manufacturing near-net shape components of high integrity directly from liquid Mg-alloys. The RDC equipment consists of two basic functional units, a twin-screw slurry maker and a standard cold chamber HPDC machine. The twin-screw slurry maker has a pair of screws rotating inside a barrel. The screws have specially designed profiles to achieve co-rotating, fully intermeshing and self-wiping. The fluid flow inside the slurry maker is characterised by high shear rate and high intensity of turbulence. The basic function of the twin-screw slurry maker is to convert the liquid metal into high quality semisolid slurry through solidification under high shear rate and high intensity of turbulence. It works in a batch manner, providing slurry every 20–30 s. During the slurry making process, there is an enormous amount of ever-changing interfacial area between the solidifying alloy, the screws and the barrel. This makes the slurry creating process extremely efficient for heat extraction. In the RDC process, a standard cold chamber HPDC machine is used to achieve the final component shaping. No modification to the HPDC machine is required. To avoid oxidation, a protective gas mixture of N_2 containing 0.4 vol.% SF_6 was used in the melting furnace and the twin-screw slurry maker.

Mg-alloy ingots (see Tables 1 and 4 for compositions) were melted at temperatures 75 °C above their liquidus and fed into the slurry maker at temperatures 50 °C above their liquidus. The slurry maker was operated at a temperature range between 585 and 630 °C depending on alloy compositions. The rotation speed of the twin-screw was set at 500 rpm, and the shearing time at 35 s. A 280 tonnes cold chamber HPDC machine was used to produce standard tensile test samples. The dimensions of the tensile test samples are 6 mm in gauge diameter, 60 mm in gauge length and 150 mm in total length. For all the experiments in this investigation, the die temperature was kept at 220 °C. Tensile tests were conducted at 10^{-3} strain rate and at room temperature.

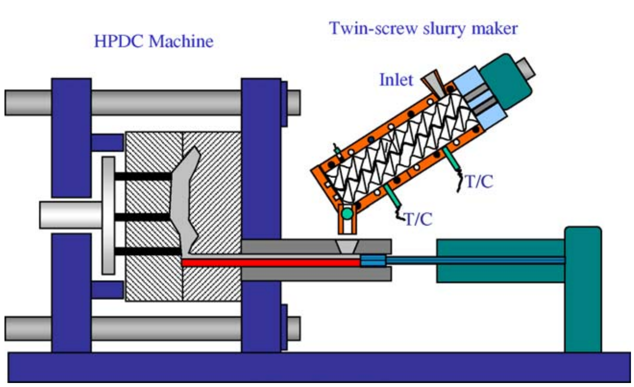

Fig. 1. Schematic illustration of the rheo-diecasting (RDC) process.

Specimens for microstructural characterisation were cut from the middle section of the tensile test samples. The microstructure of the RDC samples was examined by optical microscopy (OM) with quantitative metallography and scanning electron microscopy (SEM). The specimens for OM and SEM were prepared by the standard technique of grinding with SiC abrasive paper and polishing with an Al_3O_2 suspension solution, followed by etching in an aqueous solution of 60 vol.% ethylene glycol, 20 vol.% acetic acid and 1 vol.% concentrated HNO_3.

3. Experimental results

3.1. Microstructure of RDC Mg-alloy

The chemical compositions of the AZ91D alloy at different processing stages are presented in Table 1. There was very little change in the compositions of the alloying elements. Perhaps more importantly, there was little change in Fe content after both melting and rheo-diecasting, with the Fe content in the RDC sample being well within the specification of AZ91D alloy.

One of the most important features of SSM processing is the ability to achieve laminar die filling. To check this, the die cavity was deliberately filled half way so that the conditions at the flow front could be examined. The photograph of the half filled sample and the microstructure at the flow front are presented in Fig. 2. Fig. 2 reveals that the flow front during the mould filling was parabolic and smooth, indicating that the mould filling was laminar under the optimised conditions. In addition, the sample surface was sharp and tidy (Fig. 2c), indicating a very good surface finish produced by the RDC process.

Fig. 3 presents a montage of micrographs showing the as-cast microstructure through the entire cross-section of a 6 mm AZ91D alloy bar produced by the RDC process at 593 °C. The primary particles in the RDC samples were fine and spheroidal in nature, and distributed largely uniformly throughout the entire cross-section of the samples. There was no entrapped gas porosity, and only very fine hot cracks (a few micron in size) could be observed occasionally. The total porosity was typically 0.1–0.3%.

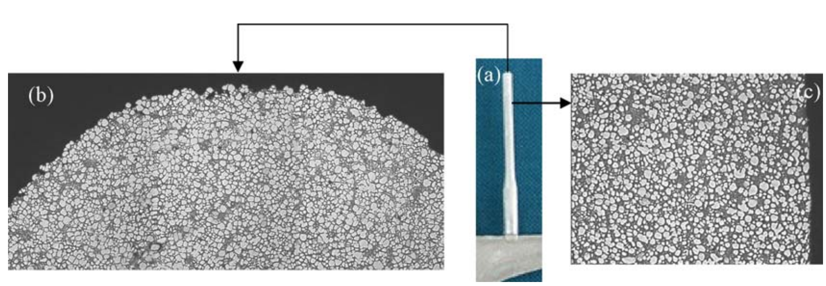

Fig. 2. Photograph of a half filled test bar (a) and micrographs showing the laminar flow front during mould filling (b) and the surface condition (c) produced by the RDC process.