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Microstructural refinement of AZ91D die-cast alloy by intensive shearing

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ABSTRACT

The melt conditioned high pressure die casting (MC-HPDC) process is introduced, where Mg-alloy AZ91D was intensively sheared at different temperatures over the liquidus temperature using the melt conditioning by advanced shear technology (MCAST) process prior to high pressure die casting (HPDC). The resultant microstructures were investigated and compared to those obtained from conventional HPDC. This study shows for the first time that the implementation of intensive shearing in the fully liquid state has produced high integrity Mg-alloy castings with fine and uniform microstructure, reduced cast defects and improved mechanical properties.

1. Introduction

Magnesium alloys, as the lightest of all structural metallic materials, have found increased application, especially in the automotive industry, triggered by the demand for vehicle weight reduction. In 2007, 32% of overall magnesium consumption in the United States was for die-casting applications whilst the global demand has been expected to increase at a 7.3% average annual growth rate until 2012 [1]. The most commonly used fabrication process for automotive components is high pressure die casting (HPDC) and AZ91D is the mostly used Mg–Al based alloy.

However, AZ91D alloy has a wide solidification interval and is highly susceptible to casting defects. As a result, the current cast components usually exhibit a coarse and non-uniform microstructure, containing various casting defects and severe chemical segregation. A very common defect in HPDC Mg-alloy components is the formation of segregation and/or porosity bands, commonly referred to as 'defect' bands, which follow contours parallel to the surface of the casting [2–6]. Solidification of the liquid metal will start as it fills the shot sleeve. The primary solid crystals that form in the cold shot sleeve, known as Externally Solidified Crystals (ESCs), get transported to the die where solidification takes place for the remaining liquid. ESCs remain in the final cast product and their volume concentration, governed by the temperature of the melt in the shot sleeve, can be influenced by several parameters, such as liquid metal superheat, heat transfer coefficient, and surface properties of the shot sleeve and alloy composition [4].

Casting defects like shrinkage porosity and hot tearing can be reduced by grain refinement, also improving the machinability of cast products [7]. Furthermore, as shown by the Hall–Petch equation, a fine grain structure is generally desirable to improve the mechanical properties [8,9]. Several researchers have pursued either a chemical or a physical approach for the grain refinement of Mg-alloys. The chemical route involves the inoculation of the alloys by adding elements such as carbon (C) [10–13], zirconium (Zr) [14], silicon carbide (SiC) [11,15], strontium (Sr) [16,17], calcium (Ca) [18] and manganese (Mn) [19]. Although grain refinement by inoculation is a route easily applicable, a universal grain refiner for Mg-alloys has not yet been identified. Finding the right inoculants for different alloy systems is not always possible and although these elements can refine the microstructure, they give rise to various other problems. The addition of carbon containing agents (C_2Cl_6 and CCl_4) can cause environmental problems [13]; Sr addition reduces the ambient temperature properties [20], whereas Ca addition promotes hot tearing [21]. Therefore, a physical route which does not involve addition of any elements is necessary. Different approaches for the grain refinement of Mg-alloys so far have seen the application of electromagnetic stirring [12,16], superheating [22] and ultrasonic vibration [23,24]. However, further research is required to reveal the mechanisms of grain refinement and these processes still need to be developed for large scale industrial application.

A grand challenge is to develop solidification processing technologies which can ensure a fine and uniform as-cast microstructure free of macro-segregation and cast defects, so that the cast products can be either directly used in the as-cast state, or only require minimal thermo-mechanical processing. Various semisolid metal processing technologies have been developed to

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refine the microstructure [25]. However, these rheo-processes have not been widely commercialized due to problems associated mainly with processability. From this point of view, it is important that such a microstructural refinement can also be obtained directly from the liquid processing route.

The implementation of the shearing is carried out by the melt conditioning by advanced shear technology (MCAST) process, involving a specially designed twin screw machine which can be directly attached to a standard HPDC machine. The twin screw mechanism is used to impose the high shearing dispersive mixing action to the melt, so that the melt is treated in such a way that its uniformity in chemistry and temperature is improved. In the melt conditioned high pressure die casting (MC-HPDC) process [26], intensive shearing can be directly imposed on the alloy melt in either liquid or semisolid state, prior to die-filling. Inside the barrel of the twin screw machine, there is a pair of specially designed screws, co-rotating, fully intermeshing and self-wiping, creating an environment of high shear rate and high intensity of turbulence for the alloy melt. The sheared melt is then cast by the conventional HPDC process and is expected to offer unique solidification behavior, and an improved fluidity and die-filling during the subsequent HPDC process. The characteristics of the process for manufacturing Mg- and Al-alloys have been investigated in the semisolid shearing domain [27–30]. In this study, we investigate the effects of intensive shearing in the fully liquid region. We demonstrate that intensive shearing of AZ91D alloy above the liquidus temperature, where the alloy has extremely good fluidity, can result in refined microstructures

2. Experimental

A top loaded electrical resistance furnace was used to melt the AZ91D alloy in a steel crucible, under a protective atmosphere of pure N_2 gas containing 0.5 vol.% SF_6, and the melt was then subjected to the intensive shearing prior to casting. Detailed description of the shearing mechanism of the MCAST process can be found elsewhere [27–29]. The rotation speed of the twin screws of the melt conditioner was controlled to be 800 rpm and the temperature ranged between 605 °C and 630 °C. After the alloy was sheared for 45 s, it was directly transferred to a standard 280-ton cold chamber HPDC machine (LK® Machinery Co. Ltd., Hong Kong) which was used to produce the standard tensile test specimen, 6.4 mm in gauge diameter and 25 mm in gauge length. Specimens for optical microscopy (OM) were cut from the top, middle and bottom sections of the gauge length of the tensile test components. The metallographic specimen for OM were prepared by grinding with SiC abrasive paper and polishing with an Al_2O_3 suspension solution, followed by etching in a solution of 5 vol.% concentrated HNO_3 and 95 vol.% ethanol. A Carl Zeiss Axioskop 2 MAT optical imaging system equipped with image analysis software was used for the OM observation and the quantitative measurements of microstructural features. In order to obtain further microstructural information, color etching in a solution of 70 ml ethanol, 10 ml water, 20 ml acetic acid and 4.2 g picric acid was used, with the colored orientation contrast being created under polarized light of the Zeiss optical microscope. Quantitative metallographic analysis was carried out to analyze the grain size and area fraction primary Mg-grains. In the process of microstructural characterization, the equivalent circle diameter d was calculated by:

$$d = \sqrt{\frac{4A}{\pi}}, \tag{1}$$

where A is the total area occupied by the grain. Finally, the mechanical properties were measured at room temperature by a universal materials tensile testing machine (Instron® 5569) at a crosshead speed of 1 mm/min (strain rate: $0.66 \times 10^{-3}\ s^{-1}$).

3. Results

Fig. 1 shows a comparison between the solidification microstructure of the AZ91D alloy prepared by HPDC and MC-HPDC process, respectively. For the HPDC processed alloy in Fig. 1(a), large and well developed dendrites are clearly visible, and the alloy also exhibited segregation of the primary Mg phase, resulting in a non-uniform microstructure. Macro-pores were often observed in the centre of the sample. Two types of dendrites were found, distinguishable by their dendrite arm spacing. During the HPDC process, the liquid stays for a few seconds in the shot sleeve (pouring) and then is injected into the die with the solidification being accomplished inside the die cavity. Some of the dendrites that form in the shot sleeve are fragmented as they are pushed through the die gate and can be seen in the final microstructure in the form of dendrite fragments or shells.

The well developed, coarse dendrites with the smaller arm spacing, seen in Fig. 1(a), were formed in the die cavity of the HPDC unit. On the other hand, the AZ91D alloy prepared by the MC-HPDC process exhibited a significant improvement in both microstructural uniformity and refinement, as shown in Fig. 1(b). The primary Mg phase was uniformly distributed across the whole sample, whilst

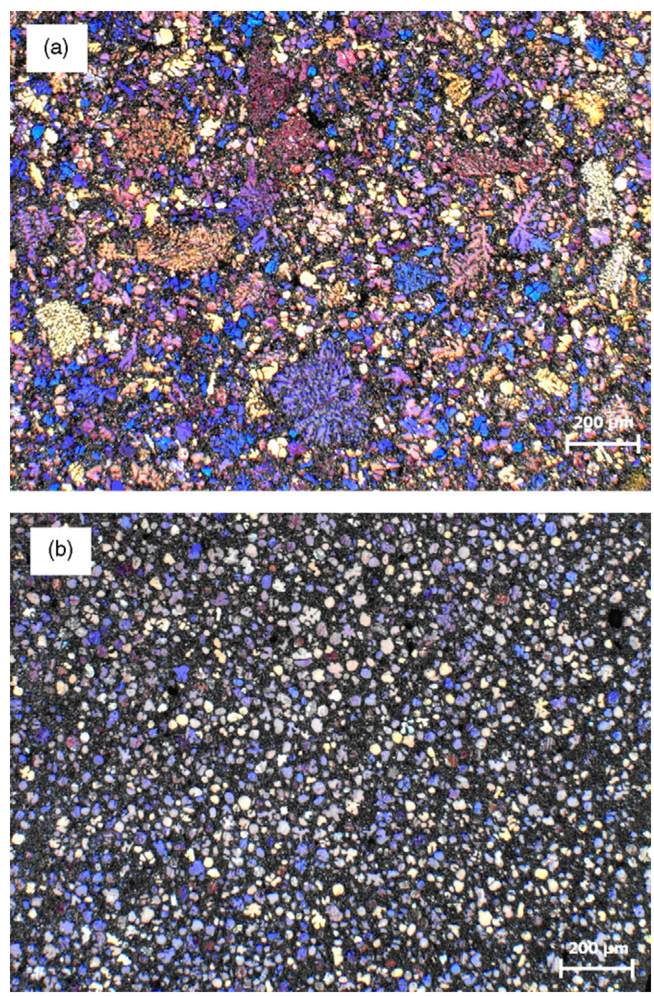

Fig. 1. Polarized optical micrograph showing the detailed solidification microstructure at the centre of the gauge length and diameter of an AZ91D alloy sample processed at 605 °C by (a) the HPDC and (b) the MC-HPDC process, respectively.