



Microstructure and mechanical properties of SiC particle reinforced magnesium composites processed by injection molding

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ARTICLE INFO

Article history:

Received 26 February 2011

Received in revised form 28 April 2011

Accepted 28 April 2011

Available online 6 May 2011

Keywords:

MMC

Magnesium injection molding

Particle reinforcement

AZ91

AJ62

SiC

ABSTRACT

The microstructure and the mechanical properties of AZ91 and AJ62 reinforced with SiC particles processed by magnesium injection molding were investigated. As a starting point, melt stirring experiments were carried out on a small laboratory scale. In both processes, injection molding and melt stirring, the particles were found to be distributed homogeneously within the matrix. Reactions between matrix and reinforcement could be prevented by employing appropriate processing temperatures. The mechanical properties of the magnesium alloys could be significantly improved by the incorporation of SiC particles. Concerning the yield strength, the contributions of various strengthening mechanisms will be discussed in the paper. Based on the strength calculations, recommendations are given on how to further optimize the mechanical properties.

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1. Introduction

Against the background of climate change, increasing CO₂ emissions, rising energy prices, and the need to preserve natural resources, lightweight design is an important factor in the current automobile development. In this context, conceptual weight reduction and weight reduction by selecting appropriate materials with low densities are of particular importance [1,2]. Since magnesium is the lightest, structural metallic material with a density of 1.74 g/cm³, a growing number of applications can be found in the automotive sector. For structural parts conventional die casting alloys such as AZ91, AM60 or AM50 are used. For power train applications especially creep resistant alloys are employed. The alloy AJ62 was chosen for the current BMW 6-cylinder magnesium aluminum composite crankcase [3] whereas AS31 is used for gearbox housings from Daimler [4].

However, compared to other light metals such as aluminum alloys, magnesium reveals lower Young's modulus, lower strength and lower wear resistance which limit the field of possible applications. An approach to overcome these drawbacks is the incorporation of harder and stiffer ceramic particles in the matrix [5]. For example, the addition of 15 vol.% SiC particles to the alloy AZ91 resulted in an improvement of the Young's modulus

by 40% [6]. Furthermore, the yield strength could be enhanced by 20%.

In recent decades several attempts have been made to produce particle reinforced magnesium alloys. These include mainly powder metallurgical routes [7–12] and casting processes [13–19], which are preferable for the large-scale fabrication of components with sophisticated geometries.

For most casting routes, such as Rheocasting [6], Compocasting [6], die casting [14] or stir casting [15], the particles have to be dispersed homogeneously in the matrix prior to casting. The difference between these processes is the applied temperature range during processing. Concerning stir casting and die casting, particle incorporation and casting is done in the fully liquid state of the matrix alloy. In contrast, when using Rheocasting or Compocasting, the reinforcement is added into the partially solidified melt. The casting is subsequently done in the partially solidified state (Rheocasting) or the fully liquid state (Compocasting).

The fabrication of reinforced magnesium alloys, using conventional casting processes, did encounter several problems in the past. On the one hand, mixing forces were not sufficient to prevent settling of the particles in the crucible and to break up particle agglomerates completely [6,15]. On the other hand, stirring at high temperatures led to gas entrapment and elevated porosity [6]. Furthermore, the combination of high temperatures and long dwell periods during mixing promoted reactions between metal matrix and reinforcement [6,14,15].

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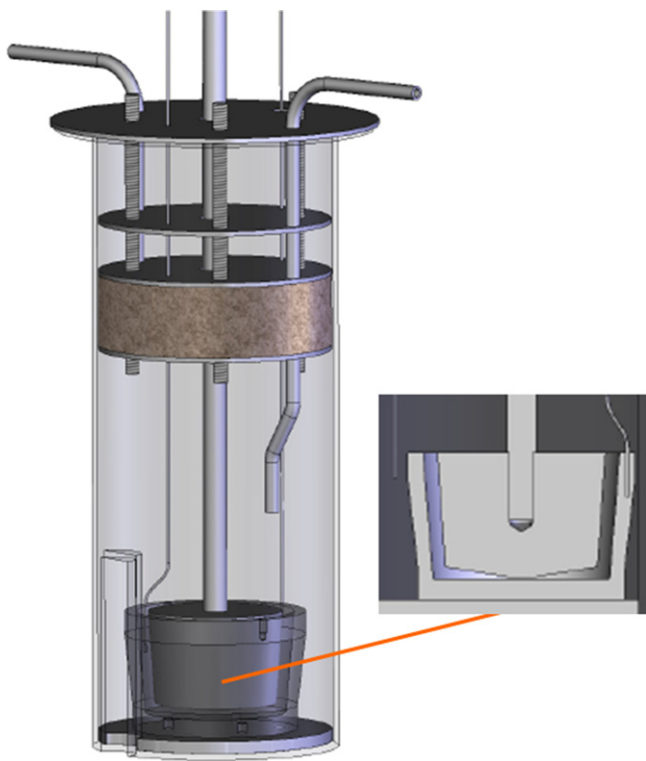


Fig. 1. Schematic drawing of the experimental setup used for the fabrication of laboratory samples, designated permanent mold casting throughout the text.

In this regard, magnesium injection molding that is pursued in the present paper, offers several benefits. Similar to injection molding machines for plastics, magnesium granules are metered into a screw. Within the screw the material is heated up to the desired temperature range while it is transported to the nozzle and subsequently injected into a die. A detailed description of the process is given in [20].

When applying magnesium injection molding, reactions between the particles and the matrix may be avoided due to the low processing temperatures and short contact times compared to die casting or other casting processes based on melt preparation in large crucibles. Additionally, the intense mixing within the screw contributes to a homogenous distribution of the particles in the matrix and avoids particle agglomeration and settling [20].

In this study, melt stirring experiments were carried out on a laboratory scale to identify the potential of the alloys AZ91 and AJ62 reinforced with SiC particles and to verify suitable processing parameters. In addition, the microstructure and mechanical properties of these materials, processed by magnesium injection molding, are presented and compared to the unreinforced alloys. The strengthening mechanisms are discussed.

2. Experimental procedure

The matrix materials AZ91 and AJ62 were received from a commercial vendor, Ecka Granules, as chips. SiC particles F 600 with a mean diameter of 9.3 microns from ESK SiC GmbH served as reinforcing phase.

Fig. 1 shows the experimental setup used for the fabrication of laboratory samples under argon atmosphere. The chips and the particles were mixed manually before putting them into the crucible. Subsequent to heating-up and melting of the matrix alloy, the particles were dispersed in the matrix alloy using a defined shear strain in the gap between rotor and crucible. The process temperatures were adapted to the conditions in magnesium injection molding

and ranged from 595 to 630 °C, which is the maximum operating temperature for a magnesium injection molding machine. Due to the high viscosity of the mixture containing high particle contents, temperatures below 595 °C were not employed. A shear rate of 100 1/s was applied for 10 min before pouring the mixture into a steel mold preheated to 150 °C. The specimens exhibited particle contents from 0 to 25 vol.%, in some cases even up to 35 vol.%.

The granulate material for the casting trials was produced by using melt stirring technique. The SiC particles were incorporated into the partially solidified melt (14 vol.% SiC at 590–595 °C for AZ91 and 12 and 20 vol.% SiC at 605–610 °C for AJ62). Subsequently, the obtained ingots were milled.

Casting trials were conducted on a 220 t Thixomolding® machine from Japan Steel Works using a mold for two separately cast tensile bars according to ASTM B557–02a. The bars exhibited a gauge length of 50.8 mm and a diameter of 6.2 mm. The barrel temperature was set to 605 °C for the alloy AZ91 and 615 °C for AJ62, i.e. both alloys were cast in the fully liquid state. A die temperature of 125 °C was applied.

For micro structural analysis, metallographic specimens were prepared and examined by optical microscope. The grain size was investigated using linear intercept method. Vickers Hardness HV1 was measured with a LECO LM30AT micro hardness tester. A load of 9.81 N was applied for 15 s. Young's Modulus was determined by impulse excitation technique according to ASTM E 1876–01. The cylindrical specimens ($\varnothing = 5$ mm, $l = 50$ mm) were either machined out of the gauge length of the tensile bars or the test bars cast in our machine shop. Standard tensile and compressive tests were carried out using a Zwick/Roell Z100 universal testing machine. The specimens for the compression tests revealed a diameter of 5 mm at a height of 7 mm.

3. Results

3.1. Microstructure

Fig. 2 illustrates the microstructure of AZ91 reinforced with SiC particles. Casting was done in the lab process according to Fig. 1 termed permanent mold casting in the following. The temperature was set below the liquidus temperature at 595 °C. The primary α -phase reveals a globular shape, similar to semi-solid processing in magnesium injection molding. The particles are almost exclusively incorporated into the residual melt, which solidifies forming dendritic secondary α - and eutectic phase (tertiary α - + $\text{Mg}_{17}\text{Al}_{12}$ -phase).

Fig. 3 shows the microstructure of the same sample after annealing at 150 °C for 200 h. Due to the enrichment of the liquid phase with Al during solidification the outer regions of the secondary α -grains are supersaturated with Al. In these areas the precipitation of $\text{Mg}_{17}\text{Al}_{12}$ occurs during heat treatment. Nearly all particles are surrounded by $\text{Mg}_{17}\text{Al}_{12}$ -phase. Therefore, we can conclude that the vast majority of the particles was rejected by the solidification front and subsequently pushed into the interdendritic regions. This result also agrees with other research, in which SiC particle pushing is reported for the melt metallurgical fabrication of particle reinforced aluminum [13] or magnesium alloys [6,14,15,18].

Despite the fact of particle pushing, a fairly uniform distribution of the particles in the matrix, showing no major agglomeration can be observed. According to [13] the uniform distribution results from a rapid solidification of the melt, which leads to a fine grain size of the secondary α -phase and prevents the transport of particles over large distances. Furthermore, no precipitations indicating reactions between the reinforcement and the magnesium alloy were detected.

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