

TWIN-SCREW RHEOMOULDING OF AZ91D Mg-ALLOY

S. Ji, Z. Fan, G. Liu, X. Fang, S. Song

Walfson Centre for Materials Processing
Brunel University, Uxbridge, Middlesex, UB8 3PH, UK.

ABSTRACT

Twin-screw rheomoulding is a new semisolid process for the near net shape production of metal's components. It includes the advantage combination in both die-casting and injection moulding. In this unique process, a liquid alloy is fed into a twin-screw extruder, where the alloy is intensively sheared and cooled into the interval of liquidus and solidus to produce semisolid slurry with fine primary particles of pre-determined volume fraction. The well-sheared semisolid slurry is then discharged into a shot cylinder and subsequently injected into a mould cavity for component shaping. This paper introduces the development of the prototype machine and the experimental work carried out with industrial AZ91D magnesium alloy. The operating characteristics of the newly developed machine, microstructures and mechanical properties of rheomoulded AZ91D magnesium alloy will be reported.

Key words: semi-solid, processing, rheomoulding, magnesium, properties

1 Introduction

In order to increase the competitiveness and to realise the full potential of semisolid metal (SSM) processing, many new techniques have been developed by SSM processing community in last few decades [1,2]. The newly developed twin-screw rheomoulding process for semisolid processing was introduced by authors in last SSM biennial conference at Turin [3,4]. In this process, a melted alloy is fed into a twin-screw extruder, where the alloy is intensively sheared and cooled into the interval of liquidus and solidus to produce semisolid slurry with fine and uniformly distributed primary particles of pre-determined volume fraction. The well-sheared semisolid slurry is then discharged into a shot cylinder and subsequently injected into a mould cavity for component shaping. The advantages of the twin-screw rheomoulding process include (1) high shear rate and high intensity of turbulence offered by the closely intermeshing, self-wiping twin screws to ensure finer non-dendritic microstructure; (2) low porosity of rheomoulded components; (3) thin-wall castings; (4) improved mechanical properties; (5) lower processing temperature for injection and consequently longer die life; (6) accurate dimensional control; and (7) lower overall component cost. In last two years, a new twin-screw rheomoulding machine for magnesium alloys SSM processing was developed and some experimental trials with industrial magnesium alloy AZ91D has been carried out. This paper reports the operation characteristics and processing control of the prototype machine, microstructural characteristics and mechanical properties of the rheomoulded AZ91D magnesium alloy.

2. Twin-Screw Rheomoulding Process

The twin-screw rheomoulding process is a combination of conventional die-casting and plastic injection moulding process. This innovative process is a one-step SSM processing technique, which aims to manufacture net shape components of high integrity directly from liquid alloy [4]. The process transfers the well-established high shear dispersive mixing and positive displacement pumping actions of the twin-screw extruder to the task of *in situ* creation of SSM slurry with fine and spherical solid particles followed by direct injection moulding of the SSM slurry into a die cavity.

Figure 1 illustrates schematically a twin-screw rheomoulding machine specifically designed for magnesium alloys, which consists of a liquid metal feeding system, a high shear twin-screw extruder, an injection system and a central control system. The rheomoulding process starts from feeding liquid metal with the predetermined dose from the furnace into the extruder. The liquid metal is cooled thereby to the SSM processing temperature while being mechanically sheared by a pair of closely intermeshing, self-wiping and co-rotating screws, converting the liquid into a semisolid slurry with a predetermined volume fraction of the solid phase dictated by accurate temperature control. The semisolid slurry is then injected at a controlled velocity into a preheated mould cavity. The fully solidified component is finally released from the mould. All these procedures are performed in a continuous cycle and controlled by a central control unit. In this machine, the mould clamp mechanism is similar to that used on conventional die-casting machines. The extruder system is similar to injection moulding machines, consisting of a high temperature barrel and a pair of specially designed screws. The injection system consisting of a shot cylinder, a plunger and a nozzle is a combination of die-casting machine and injection moulding machine.

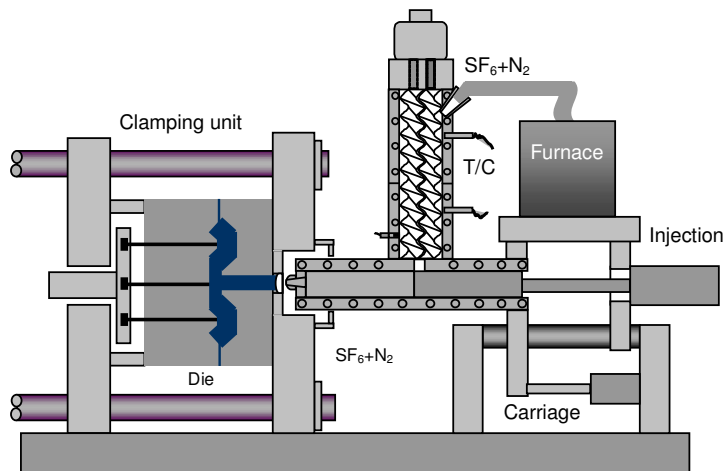


Figure 1. Schematic illustration of the twin-screw rheomoulding machine.

The liquid alloy injection temperature is set to achieve a 1-50% volume fraction of primary solids. When processing AZ91D the nominal shearing and injection temperature can be determined according to either the equilibrium phase diagram of Mg-Al alloy or

the DSC analysed curve for the alloy, usually from 575 to 600°C. The high temperature ceramic band heater is used to bring the alloy to its semisolid temperature with a proper PID control in a computer system. Few band heaters with different sizes and energy capacities are wrapped on the barrel and shot cylinder to realise the selected temperature profile for them, depending on the alloy being processed. In order to prevent magnesium alloys from oxidation during melting and rheomoulding processes,

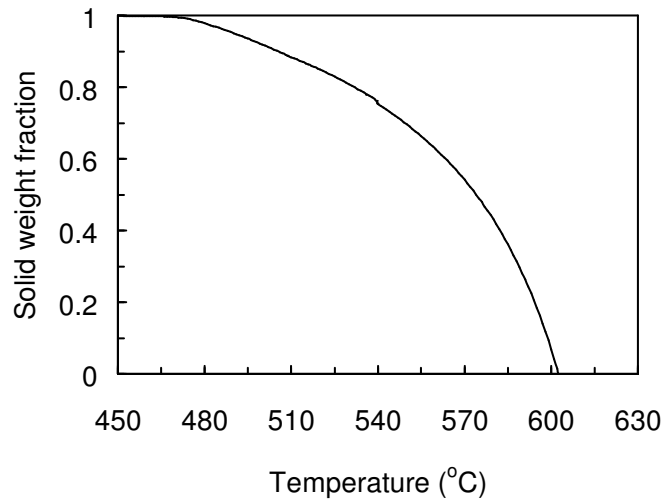


Figure 2. The relationship between temperature and the volume fraction of primary solids of AZ91D alloy calculated by Thermo-Calc software according to the composition of Mg-8.3Al-0.5Zn-0.2Mn-0.03Si-0.007Cu-0.005Ca.

a mixture of 0.1-0.6vol.% SF₆ in nitrogen is maintained in the melting furnace, the twin-screw extruder and the injection system during operation. The reciprocation of plunger positioned in shot cylinder results in the injection of semisolid slurry into the die cavity. The injection size is primarily determined by the weight of the component being produced. Obviously it should be smaller than the maximum volume of the shot cylinder. The plunger also plays a role of valve. The backward movement of plunger along the shot cylinder allows the semisolid slurry transferring from extruder to shot cylinder. The forward movement of the plunger along shot cylinder drives the semisolid thixotropic slurry filling the die cavity with a desired velocity. The injection velocity is usually in excess of 250 cm/s with a metal pressure over 30MPa.

During rheomoulding of magnesium alloys, few things should be carefully controlled, including the enhancement of the high quality of semisolid slurry and the cleanness of processing environments. The essential criterion for high quality semisolid slurry is the accurate control of temperature. The specially designed band heaters control the uniformity of semisolid slurry in the barrel and the shot cylinder. The inaccurate control of temperature would result in difficulty during processing. The close temperature control for the shot cylinder is more important to achieve the process consistent because of the remnant of semisolid slurry therein during operation. The cleanness of the screw, inner barrel and shot cylinder is also important to keep the process consistent and to reduce the inclusion during processing.

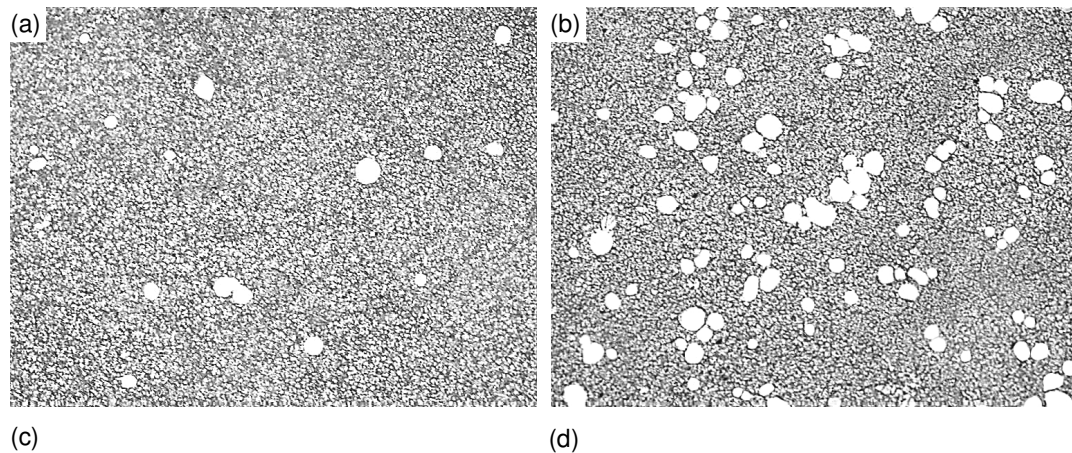
The first prototype of twin-screw rheomoulding machine was built by Rheomatix, UK. This development has a 30-ton die clamp and injection pressure up to 120MPa. The twin-screw extruder has been designed to process 550g AZ91D magnesium alloy per cycle and to permit a twenty seconds injection cycle for processing. The machine was driven by hydraulic system with a PLC control system. **Figure 3** shows the rheomoulded AZ91D alloy components designed for experiments. The square sample for impact test is in zero draft dies and without difficult in operation.



Figure 3. Photograph of the rheomoulded AZ91D alloy component.

3 Microstructure of rheomoulded AZ91D alloy

Figure 4 shows the optical micrographs of rheomoulded AZ91D magnesium alloy sheared with a shear rate of 225s^{-1} for 30s before injection. The solid particles have a spherical morphology, uniform distribution and fine particle size with the average size from 60 to $80\mu\text{m}$ for different volume fraction of solids, which is much smaller than that produced by other available techniques. It is most significant that the twin-screw rheomoulding can produce small and uniformly distributed primary particles at very low volume fraction. In addition, the preliminary results have demonstrated that this process is capable of manufacturing near-net shape components with close to zero porosity.



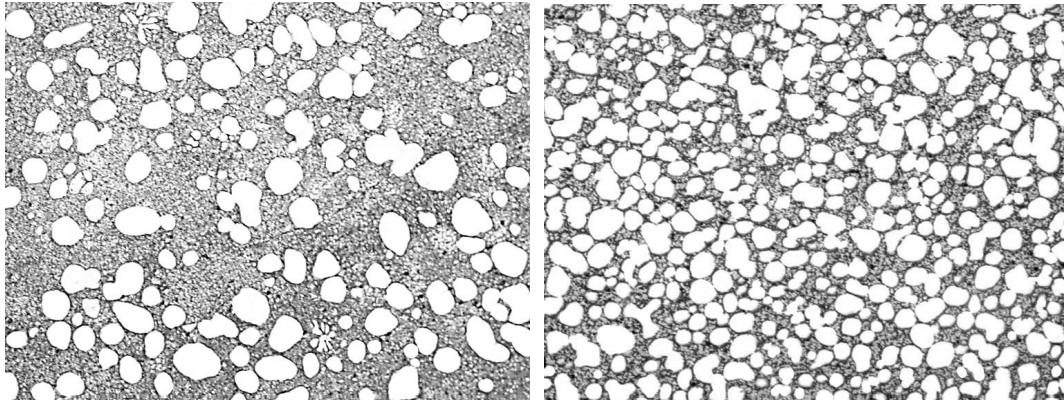


Figure 4. Optical micrographs showing the microstructure of rheomoulded AZ91D alloy with different volume fraction of primary particles sheared with a shear rate of $225s^{-1}$ for 30s before injection. (a) $f_s=2\%$; (b) $f_s=11\%$; (c) $f_s=30\%$; (4) $f_s=51\%$.

It has been long believed that the non-dendritic particles are developed from the initial dendritic morphology under dynamic agitation [5]. The initial dendrites are fragmented through dendrite arm detachment by either a shear force or re-melting at the dendrite arm roots. With increasing shearing time, the fragmented dendrite arms change gradually to spheroids via dendrite growth, rosettes and ripening. However, the authors recent experimental work and theoretical analysis of the morphological evolution of solid phase [6, 7] revealed that the above mechanism may be only applicable to the case of a simple shear flow with low shear rate. With increasing shear rate and the intensity of turbulence, the growth morphology changes from dendritic to spherical via rosette.

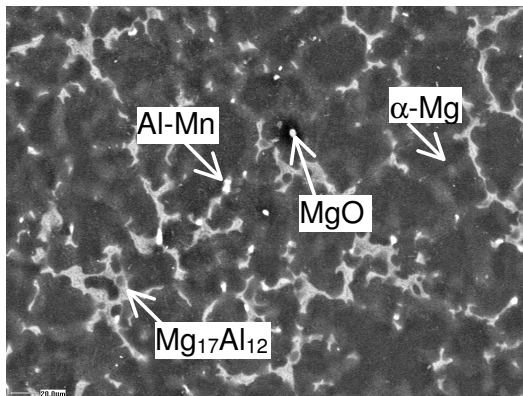


Figure 5. Backscattered SEM micrograph showing the matrix of rheomoulded AZ91D alloy sheared with a shear rate of $225s^{-1}$ for 30s before injection

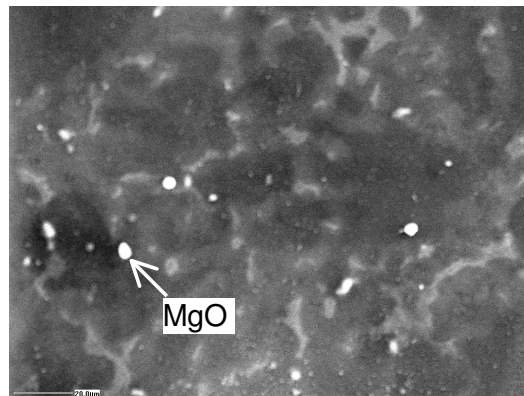


Figure 6. SEM micrograph showing the matrix of rheomoulded AZ91D alloy sheared with a shear rate of $225s^{-1}$ for 30s before injection.

Figure 7 shows the particle distribution across a section of rheomoulded AZ91D alloy sheared with a shear rate of $225s^{-1}$ for 30s before injection. Obviously, the primary particles tend to accumulate close the centre of the section. The volume fraction of the primary particles at centre area is 51%, but at side area is from 15% to 25%. The filling velocity mainly controls the variation of the primary particles across the section. Ideally, the semisolid slurry should fill the die as quickly as possible without creating critical particle separation. The extreme filling velocity can result in particle separation because the liquid phase moves out in front of the solid phase.

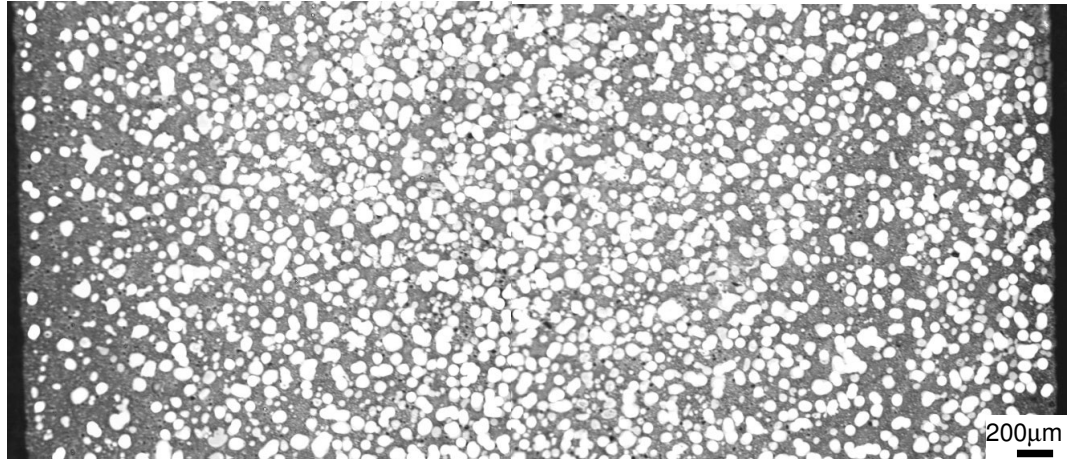


Figure 7. Optical micrographs showing the distribution of primary particles of rheomoulded AZ91D alloy sheared with a shear rate of $225s^{-1}$ for 30s before injection.

4 Mechanical Properties

Table 1 illustrates the mechanical properties of AZ91D alloy rheomoulded at different temperatures, corresponding to different volume fractions of primary particles. The tensile strength was directly tested with as-moulded samples of 6mm in diameter. The results illustrated that the ultimate tensile strength reduces with increasing volume fraction of primary particles, which is similar to other's observation in Thixomoulding [8,9]. The tensile strength of rheomoulded AZ91D alloy is temporarily below the die-casting specification due mainly to the un-optimised processing parameters. Work continues to further development to realise the full potential of rheomoulding process.

Table 1. The mechanical properties of rheomoulded AZ91D alloy sheared with a shear rate of $225s^{-1}$ for 30s before injection

Volume fraction of primary particles (%)	Mean size of primary particles (μm)	Ultimate tensile strength ^a (MPa)	Elongation ^a (%)	Impact resistance ^b (J)
0.5	76	205.8	1.9	10.7
0.9	70	204.1	1.8	7.6
1.0	69	209.2	2.0	12.9

2.0	64	206.2	1.7	11.9
3.5	74	202.3	1.9	>15.0
12	61	203.0	2.0	12.6
30	71	188.0	1.6	10.7
51	67	175.4	1.2	7.3

^a – At 25±2°C, ϕ 6mm bar with gauge length of 25mm.

^b – ASTM E23 un-notched 10mm as-moulded square bar.

5 Processes comparison

Compared with high pressure die-casting process, the advantages of twin-screw rheomoulding process include (1) high component integrity with close to zero porosity; (2) lower scrap rate and tighter dimensional control; (3) suitable for safety crucial and pressure tight components; (4) lower SSM temperature for injection and consequently longer die life; (5) accurate temperature control and thus better microstructural uniformity (6) higher materials yield; and (7) lower overall component production cost.

Compared with thixomoulding process, the advantages of twin-screw rheomoulding process include (1) easy and steady material feeding; (2) longer screw life; (3) higher shear rate resulting in finer primary particles; (4) in-house recycling of scrap casting and residues; (5) lower energy consumption; (6) lower overall component production cost.

6 Summary

Twin-screw rheomoulding is a new process for the net shape of semisolid metal. It combines the advantages in both die-casting and injection moulding. A unique characteristic of twin-screw rheomoulding is the fine and uniformly distributed primary particles and the significantly reduced porosity level resulted from the utilisation of a specially designed twin-screw extruder for semi-solid slurry production under high shear rate and high intensity of turbulence. The low porosity in the as-moulded component will allow the heat treatment for the further optimisation of the mechanical properties.

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