Magnesium alloy particulates for Thixomolding applications manufactured by rapid solidification

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Received 7 August 2003; received in revised form 4 October 2003

Abstract

Techniques based on a rapid solidification concept were explored for manufacturing particulates of magnesium alloys with the potential use as feedstock for Thixomolding®. Basic features of granulation methods are outlined along with dimensional, morphological, microstructural and chemical characterizations of particulates with a composition of Mg–9% Al–1% Zn. In spite of the known tendency of Mg and Zn to evaporate, the globule chemistry was within the alloy’s specification. The microstructure comprised of dendritic morphologies of α-Mg and Mg₁₇Al₁₂ phases where the content of the latter was reduced compared to the conventionally cast state. It is suggested that the microchemical and phase segregations which accompanied the morphology of fine equiaxed dendrites are the key factors which control the transformation of particulates during subsequent heating in a solid state and their melting behaviour.

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Keywords: Magnesium alloys; Rapid solidification; Atomization; Injection molding; Thixomolding®; Semisolid processing

1. Introduction

The continuous quest for high quality feedstock available for Thixomolding has catalyzed the development of alternatives to the presently explored technologies of mechanical comminution. In this search, particular attention is being paid to techniques based on the liquid precursor. It is anticipated that it will be possible to implement in the near future, direct manufacturing from the primary melt, omitting the ingot stage, thereby providing energy savings and reducing the final cost.

Rapid solidification is characterized by a very high cooling rate which ranges from 10⁵ to 10⁶ °C/s for convective heat transfer, to 10⁶–0.8 °C/s for conductive heat transfer mechanisms. It has been used for many Mg alloys to produce melt spun ribbons which, after mechanical comminuting into powders, were sealed in cans and extruded into bars [1]. In another application, the granules obtained by rapidly solidifying droplets of the molten alloy were subsequently compacted and extruded into various shapes [2]. Atomizing, i.e. disintegrating a liquid stream of magnesium into droplets, and freezing them into solid particulates of a spherical shape, is a method which utilizes the idea of rapid solidification. A different concept is used in the emulsification of globular salt-coated particulates, where liquid magnesium is first agitated in a boron-containing flux. On freezing, Mg particulates with a size of 10–50 mesh which emulsify as small spheres, are freed by grinding [3].

Although the idea of manufacturing particulates for Thixomolding is the same as that used for powder metallurgy, the significantly larger size required for the former imposes new challenges on the equipment and process. As a result, there is still no commercial scale manufacturing and small quantities of the feedstock are generated at the laboratory level using prototype hardware. Several types of such particulates were collected for the purpose of this study. The objective was to provide detailed characterizations of Mg alloy particulates obtained from a liquid precursor by exploring techniques based on a rapid solidification, and define features which make them useful for Thixomolding applications.

2. Manufacturing technologies

Depending on the final destination and particulate size, there are several modifications of atomization techniques.
widely used for the manufacturing of a large tonnage of powders. Since, for injection molding, relatively large particulates with a size typically over 0.5 mm are required, the technique is frequently referred to as granulation instead of atomization. This section contains experimental details of technologies used for manufacturing particulates described in this study.

2.1. Atomization/granulation

2.1.1. Inert gas or liquid cooling apparatus

Conventional atomization methods allow the production of granules mostly in the size range of 0.2–1 mm, depending on the apparatus’ height. In this technique the liquid stream of molten metal is fed vertically down to the nozzle which is located at the top of the tower [4]. As the metal stream exits the nozzle, it is struck by a high velocity stream of an atomizing medium, e.g. inert gas. As a result, the molten metal is disintegrated into fine droplets which solidify during the fall through the apparatus tower. Since inert gases such as helium or argon have poor cooling properties, the solidification time is long and a magnesium droplet of 1 mm requires a tower of about 7 m high. For larger diameters, the problem is more severe and a droplet with a diameter of 2 mm requires a tower with a height of 21 m. Other frequently quoted disadvantages of using an inert gas are: the large volumes of gases required and related cost; use of an inert gas enhances the evaporation of Mg from the alloy and the reactivity of magnesium with gas impurities [4].

In order to overcome the above limitations, an apparatus based on the liquid quenching concept was developed [5]. The metal is fed under high pressure into the nozzle which disintegrates it into small droplets, and the droplets are formed in argon, helium or other inert gases at a pressure of 0.1 MPa (1 atm) and very low oxygen and vapour concentrations. The droplets are subsequently solidified and cooled in an inert bath, e.g. a non-polar oil continuously stirred, cooled externally and kept at a temperature of 5–200 °C. Alternatively, centrifugal force can be used to break up the liquid as it is removed from the nozzle of a rotating electrode or spinning disk.

![Fig. 1. The morphology of particulates obtained from a liquid precursor by various methods of atomization/granulation: (a) G1: inverted stream apparatus; (b) G2: argon gas system; (c) G3: inverted stream apparatus; (d) G4: large droplets casting with a liquid or gas quench; (e) G5: large droplets casting with a quench in a fluidized sand bed.](image-url)
Table 1
The particulate size distributions determined by screen analysis according to ASTM specification E276-68

<table>
<thead>
<tr>
<th>Particulate type</th>
<th>Shape type</th>
<th>Alloy grade</th>
<th>Sieve opening (mm)</th>
<th>Apparent density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.75</td>
<td>3.38</td>
</tr>
<tr>
<td>Granules G1</td>
<td>AZ91D</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>G2</td>
<td>AZ91D</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>G3</td>
<td>AZ91D</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>G4</td>
<td>AZ91D</td>
<td></td>
<td>76.1</td>
<td>23.5</td>
</tr>
<tr>
<td>GD2</td>
<td>AZ91D</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table values represent weight fractions in percentage retained by sieves of given opening.

2.1.2. Inverted stream apparatus

The unique feature of the inverted stream apparatus is the positioning of a nozzle at the bottom of the cooling chamber [6]. During their upward trajectory, the streams break up into droplets which solidify substantially before landing on a collector plate at the base. Due to the parabolic trajectory of the droplets over a 2 m vertical displacement, it is approximately five times longer than a free fall, thus significantly increasing the cooling time. The prototype tower, built at the Alberta Research Council, has dimensions of 6 m × 1.2 m × 1.2 m and is capable of generating spherical granules up to about 4 mm in diameter at a rate of 15 kg/h with a yield of 97–99%. Up to 50 kg of metal is melted in a resistance furnace located in the containment vessel on the bottom. The vessel is pressurized between 100 and 200 kPa gauge and at least one stream of a molten metal is generated upwards through a nozzle. The nozzle is vibrating at a high frequency transverse to the fluid stream to cause a periodic dispersion of the segmental droplet trajectory, preventing the droplets from impacting each other and coalescing. Most of the granules produced are immediately removed from the collector. At steady-state conditions, the inner temperature of the tower is as high as 100 °C. The tower is cooled due to heat radiation from the steel walls and also by recirculating gas through heat exchangers. There are a number of advantages to this process including: it does not require SF6 or corrosive protective gases such as SO2, it does not require an oil quench and has the possibility of using a recycled argon atmosphere.

2.2. Casting of large droplets

There are techniques to produce relatively large granules with a size exceeding several millimeters by the mechanical break up of a liquid stream of Mg alloy into droplets. As a source of liquid alloy either furnaces or screw extruders are used. In these systems, the cooling towers are eliminated and large metal droplets are formed just above the quenching medium, most frequently a liquid. Alternatively, quenching may be conducted using fluidized sand bed.
3. Characterization of granules

3.1. Dimensional and morphological features

Thixomolding application requires relatively coarse particulates and their diameter should be of the order of millimeters as opposed to micrometers, as is used in powder metallurgy. Several examples of granules, manufactured using techniques described in Section 2, are shown in Fig. 1. The granules with smaller sizes, shown in Fig. 1a–c, were obtained in granulation towers. The majority of them have a shiny metallic color characteristic for the oxide-free surface. However, some particulates, especially among those of the G2 type, exhibited dark oxidized surfaces. The correlation exists between the particulate size and surface colour with larger particulates experiencing more surface oxidation (Fig. 1b). The significantly larger granules shown in Fig. 1d and e were obtained by direct casting of the alloy droplets followed by quenching in a liquid or gas (G4) and in a fluidized sand bed (G5).

The major difference between granules examined here is their size and its distribution. The summary of sieve analysis is given in Table 1 with plots of selected granules compared in Fig. 2. For the smallest granules G1, shown in Fig. 1a, a fraction of 90% was retained by the sieve with an opening of 0.6 mm. The remaining portion was retained on sieves with openings between 2.36 mm and completely solid. A different distribution was found for globules G2 where sizes were split almost equally between sieves of 0.6 and 1.3 mm. For granules G3, the maximum fraction was retained by the sieve of 1.4 mm with a very small portion held by the 2.36 mm opening. The sieve analysis did not provide full characterization of large granules G4 and G5. This is expressed by the plot in Fig. 2, where almost all G4 granules were retained by the largest sieve opening of 4.74 mm, i.e. they remained outside the sieve sizes employed. Therefore, an additional characterization was introduced with a direct measurement under a magnification of over 200 granules. According to this measurement, the average diameter of the G4 granules is 5.93 mm with a relatively wide distribution profile and a maximum of 35% around a diameter of 6 mm (Fig. 3). The visually larger G5 granules are characterized by an average diameter of 8.93 mm. Their distribution profile has a maximum of 57% at the location close to the average value.

The apparent density is of importance for the particulates’ transportation, feeding the injection system, conveying them along machine barrel as well as heat transfer and melting rate. A value equal to half of the ingot density is often quoted...
as a threshold required to fulfill the above requirements. For all types of granules examined here, the apparent density was between 1.008 and 1.127 g/cm³ with no evident correlation with their size (Table 1). Since this is over 0.5 of the AZ91D alloy density being of 1.81 g/cm³, granules met the condition of minimum density. This value is also generally larger than a density of mechanically comminuted chips.

3.2. External defects

There are numerous defects created at the manufacturing stage, and the most frequent of them include (i) spherical shape distortion, (ii) agglomeration and (iii) surface deterioration through reactions with impurities in the gases inside the granulation tower [5]. Because individual droplets spheroidize from a ligand shape, as a result of the break up of a liquid stream, too fast a solidification prior to spheroidization generates irregularly shaped particulates. In contrast, too slow a solidification, combined with a lack of sufficient separation between particulates, causes their agglomeration. Shape deviations are seen within particulates which, according to visual assessment, appeared to be highly spheroidal (Fig. 4). An interaction was taking place between particulates which traveled in liquid and semisolid states during granulation. As a result, the particulates at the initial and well-advanced coalescence stages were occasionally observed. An extreme case of shape deviation is shown in Fig. 5a where particulates marked as GD1 reached a form...
of whiskers with a diameter of 0.8–1 mm and a length up to 20 mm. Frequently, the whiskers had a spherical particle attached to their end. Since their surfaces are shiny metallic it excludes an oxidizing reaction as the key cause of shape defect. At this stage, exact cause of their origin is not clear.

Prevention of surface deterioration during granulation is of particular importance for magnesium alloys, known for their high affinity to oxygen [7]. There are reports that even for a granulation environment of high purity He, the oxygen potential was still high enough to cause a reaction, and for Al–Mg particulates with a size between 5 and 50 μm, an oxide layer with a thickness of 5 nm was formed. A moderate surface oxidation was experienced by particulates GD2 (Fig. 5b). For a fraction of granules GD2 with a spherical shape, the extent of oxidation was correlated with their size: while small granules had a shiny metallic surface, larger ones were matt and dark, indicating oxidation. There were also some particulates among GD2 with an irregular shape and surface covered with an oxide. In an extreme case of a highly oxidizing atmosphere, the oxide layer can be thick enough to make spheroidization impossible. Under such conditions, the particulates with an irregular shape and heavily oxidized surface were formed (Fig. 5c). Their size distribution, with roughly of 50% particulates retained by the sieve of 1.4 mm, is close to types designated as G1 and G3 (Table 1).

### 3.3. Stability of chemical composition

During granulation, a relatively large free surface of the liquid alloy is exposed to the gaseous atmosphere. Since certain chemical elements of magnesium alloys are known to exhibit a very high evaporation rate, the chemistry of small droplets is prone to changes. Such a phenomenon was registered during the laser melting of an AZ91D alloy where the Al content was increased to 11–12%, mainly due to the evaporation of Mg [8]. Zinc, present as a minor element in AZ91D alloy, is also affected by evaporation and its content was reduced to 0.68–0.70%. Such a strong loss occurs because zinc has a vapor pressure one order of magnitude higher than magnesium in the molten state. The reduced content of Mg led to a higher volume fraction of the Mg17Al12 phase; a phenomenon exactly opposite than should be expected based on solidification conditions [8].

The chemical analysis of selected granules is summarized in Table 2. The measurement was conducted using an inductively coupled argon plasma mass spectrometer and following ASTM E1097-97 (modified) and E1479-99 standards. It is seen that the content of all elements tested, including Al and Zn, is within the range specified by the ASTM B94 standard. Moreover, there is no difference in chemistry between particulates of different sizes. Originally, it was suspected that due to a longer solidification time and exposure to the gas atmosphere, larger G3 granules should exhibit higher deviations in chemistry than small G1 particulates.

### Table 2

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Zn</th>
<th>Mn</th>
<th>Si</th>
<th>Cu</th>
<th>Ni</th>
<th>Fe</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>8.58</td>
<td>0.79</td>
<td>0.18</td>
<td>0.02</td>
<td>0.01</td>
<td>0.001</td>
<td>0.001</td>
<td>Bal</td>
</tr>
<tr>
<td>G3</td>
<td>8.74</td>
<td>0.79</td>
<td>0.17</td>
<td>0.01</td>
<td>0.001</td>
<td>0.001</td>
<td>0.004</td>
<td>Bal</td>
</tr>
<tr>
<td>AZ91D standard ASTM B94</td>
<td>8.3–9.7</td>
<td>0.35–1.0</td>
<td>0.15</td>
<td>0.10 max</td>
<td>0.03 max</td>
<td>0.002 max</td>
<td>0.005 max</td>
<td>Bal</td>
</tr>
</tbody>
</table>

All values are in wt.%.

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Fig. 7. Optical microscope images of internal microstructures of granules G1: (a) general view and (b) magnified image with an alignment of dendrites in near surface region.
3.4. Phase composition

The principal effect of a high cooling rate during solidification is a drastic slowdown, or sometimes even complete suppression, of movement or diffusion of atoms within an alloy. As a result, atoms are prevented from occupying the equilibrium crystal sites with the lowest energy. The solubility of a solute in solid and liquid under equilibrium conditions is usually different and solute partitioning leads to segregation phenomena. However, if the solid/liquid interface advances rapidly, partitioning cannot follow and solute trapping occurs. Thus the solute content within the solid, growing from the melt, is higher than that predicted from the phase diagram. In extreme cases of very rapid solidification, there is no partitioning whatsoever and a solid forms with the same composition as the liquid [9].

In general, the Mg–9% Al–1% Zn alloy is composed of two phases: α-Mg matrix, being a solid solution of Al and Zn in Mg, and the precipitates of the equilibrium phase with a stoichiometric composition of Mg17Al12 (44.0 wt.% Al), an α-Mn type lattice and a cell parameter of 10.56 Å [10]. Under equilibrium conditions, the solubility of Al is 11.5 at.% at 427 °C, but in as-cast alloys a solid solution below 427 °C is enriched only with 3–4 at.% of Al. Compared with phases present in binary Mg–Al alloys, no new phases occur in ternary Mg–Al–Zn systems, if the Al to Zn ratio is greater than 3:1 and at no stage does AZ91D contain a ternary compound.

The diffraction pattern of rapidly solidified granules contains all peaks typical for Mg with the strongest of (1 0 1) at 2θ of 36.6° (Fig. 6). The major difference, as compared to patterns collected previously from the same alloy in the as-cast state [7,11], is the significantly higher intensity of the (0 0 2) peak from the basal planes. According to the JCPDS standard, the intensity of this peak is 41% of that for the (1 0 1) peak. Another feature of this pattern is a lack of distinct peaks for the Mg17Al12 phase. In fact, the only peak which could be ascribed to this phase is the strongest one with I/Imax of 100% and located at 2θ of 36.191°. Two remaining strong peaks with an equal intensity of 33%, located at 2θ of 40.227 and 65.186°, are difficult to extract from the background noise. Based on a comparison with previously published diffraction patterns of the same alloy, it is concluded that the volume fraction of the Mg17Al12 phase within

![Fig. 8. SEM images of microstructural details within granules: (a) general view of distribution of intermetallic phase in granule G1; (b) a detailed morphology of Mg17Al12 phase in G1; (c) cellular arrangement of intermetallic Mg17Al12 phase; (d) shrinkage porosity on the surface of granule G1.](Image)
granules is lower than 9–10% detected in the as-cast state [7,11]. At this point, the exact extent of this reduction cannot be unambiguously defined. The reduction in content of the Mg17Al12 phase is consistent with the literature observations made during melt spinning and splat quenching [12,13].

3.5. Internal microstructure

Due to rapid solidification of a small volume of the alloy, the granules developed a fine microstructure of equiaxed dendrites which were constituted of the α-Mg phase, while the Mg17Al12 (γ) compound was distributed within the interdendritic zones. Content of the γ phase is equal across the granule cross section (Fig. 7a). For G1 granules, the typical distance between the closest dendrite arms is of the order of 10–15 μm and the arrangement of dendrites suggests their random crystallographic orientation (Fig. 7b).

The detailed morphology of the α-Mg and Mg17Al12 (γ) phases is shown in Fig. 8. The γ phase contrast in the scanning electron microscopy is bright, conversely to that seen in optical microscopy (Fig. 8a). The massive precipitates of the intermetallic phase, observed under high magnification, are irregularly shaped while filling the interdendritic spaces. In the case of larger precipitates, there were internal voids and some of them likely formed due to solidification shrinkage. Some of them could also be caused by etching during sample preparation (Fig. 8b). Since the intermetallic phase γ is distributed within interdendritic spaces, it separates α-Mg and very often forms a cellular structure (Fig. 8c). The precipitates are essentially pore-free, though for larger sizes an irregular surface porosity could occasionally be seen (Fig. 8d).

The general features discussed here for granules G1 were also valid for granules G2 and G3. The major difference was a tendency of coarsening of α-Mg dendrites and an increased distance between the Mg17Al12 phase. It is assumed that in all systems dendrites begin coarsening immediately after formation [9]. During long exposures to high temperatures after solidification, the average length and shape of dendrites evolve resulting in a microstructure determined largely by the coarsening process. Therefore, it was suspected that

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Fig. 9. The influence of quenching rate on the microstructure of large granules G4 obtained by casting of large droplets: (a) granule solidified in air; (b) details of dendrites morphology from (a); (c) granule after solidification in a quenching liquid; (d) details of dendrite morphology from (c).
substantial changes could be created in the case of the larger granules G4 and G5. In fact, after solidification in air, G4 granules exhibited a much coarser microstructure and the α-Mg cell within the eutectics was of the order of 96 μm (Fig. 9a and b). Quenching in a liquid, however, for a similar size of granules, significantly refined their microstructure with the eutectic α-Mg cell size reduced to 11 μm (Fig. 9c and d). Thus by introducing more aggressive quenching media, granules with sizes up to 10 mm retained essentially the same microstructure as that observed for small granules typically below 1 mm in size.

As revealed by cross-sectional analysis, external defects did not substantially affect the granule’s internal microstructure, which in the case of the GD1 type, was slightly finer than that for the type G1 (Fig. 10a). In addition, there was some difference in the orientation of dendrites caused by the elongated shape of particulates, which affects directions of heat transfer during solidification (Fig. 10b). The shape distortion, observed for granules GD3, is most likely associated with their surface oxidation. Since the oxide blocks the heat transfer, some coarsening of internal structure was anticipated. However, even for an extensively oxidized surface such as that for granules GD3, the oxide layer is not seen as a separate phase but rather as the deterioration of the outer surface expressed by an increased roughness (Fig. 10c). Here, numerous protrusions and pits on the surface are seen under higher magnification (Fig. 10d). The internal microstructure is essentially the same as that observed for spheroidal granules. No noticeable coarsening of the microstructure was detected, which could be associated with a reduced cooling rate caused by a presence of the oxide film.

4. Features affecting Thixomolding applications

4.1. Size and morphology

Experimental verifications confirmed that granules of AZ91D alloy, obtained by rapid solidification techniques, were successfully used as a feedstock in the Husky TXM-
500-M70 Thixomolding system [14]. The near spheroidal shape and consistent size of the granules were beneficial for both the feeding and flow characteristics inside the machine barrel. An important factor which affects the application of particulates is their shape. Literature data indicate that irregular particulates are prone to block feeding devices and do not show good packing characteristics. Their irregular shape inhibits the heat transfer from the machine barrel walls thus reduces effective melting rates. Of many particulate shapes studied, including ovoid, teardrop, needle-like and cylindrical, the spheroidal shape, such as that obtained after granulation from the liquid precursor, provided the best feeding, packing and heat transfer behaviour. There is still no data on the optimum size required and granules with diameters between 0.5 mm and roughly 5 mm are considered well processable in presently used systems. It is further anticipated that larger or differently designed systems will accommodate particulates as large as 10 mm in diameter. Instead, attention is paid to size uniformity, since too wide a size distribution profile negatively affects the homogeneity of their melting.

4.2. Microstructural features

Although granule size and shape are of importance, the key factor which affects an application for semisolid processing is their ability to form a thixotropic structure in the partially remelted state. The most frequently quoted benefits of the rapid solidification include improved mechanical and chemical properties, improved creep at elevated temperatures and their thermal stability, superplastic behaviour and higher corrosion resistance [8,15]. These features, however, are not relevant for the particular application of material as a feedstock during injection molding. Our research, which was described in detail previously, showed that the fine microstructure formed during rapid solidification, which controls the above properties, is also of primary importance for controlling particulate melting behaviour [16].

The transformation of a granule microstructure during heating is shown in Fig. 11. The major changes in the solid state include spheroidization of the γ phase and the solution of Al atoms within the α-Mg matrix. At 400 °C, the

![Fig. 11. Transformation of rapidly solidified structures during sole heating:](image)
intermetallic phase forms a fine cellular network around the \(\alpha\)-Mg grains (Fig. 11a and b). After exceeding the solidus temperature, the thixotropic microstructure was formed with near spherical solid particles surrounded by regions of the former liquid (Fig. 11c). As described previously [16], the size of the globular solid particles is in the range of between 80 and 120\(\mu\)m, with a tendency to size reduction after increasing the temperature. So far there are no clear relationships between the granule size and the size of the spherical particles inside the semisolid slurry after partial re-melting. A review of the literature shows that the majority of studies in the area of semisolid processing are focused on the steps of solidification. At the same time the opposite phenomenon of melting is not fully understood. There is still no clear mechanism which describes the re-melting process of rapidly solidified structures and correlates the solid size with microstructural features of the granules. For mechanically comminuted chips, the solid size was proven to be strongly related to the alloy’s grain size in a solid state [16–18]. As opposed to cold-worked chips, for rapidly solidified granules it is not clear what parameter should be used to describe the solid state. Dendrite is a topologically complex structure. Although there were some attempts to measure three-dimensional interfacial curvature [19], at present it is described by only one average microstructural parameter, i.e. secondary dendrite-arm spacing. Thus the detailed mechanism of generation of thixotropic structure during re-melting of rapidly solidified granules is yet to be determined.

5. Conclusions

The granulation techniques based on the idea of rapid solidification allowed manufacturing near spherical particulates from an Mg–9% Al–1% Zn alloy with a wide range of sizes from 0.5 to 10 mm. Although there is a known tendency for Mg and Zn to evaporate, the granules’ chemistry was consistent with the alloy’s specification. The granules’ microstructure comprised of fine equiaxed dendrites of \(\alpha\)-Mg, with the \(\text{Mg}_2\text{Al}_12\) phase filling the interdendritic spaces. As a result of rapid solidification, the content of the \(\text{Mg}_2\text{Al}_12\) phase was reduced when compared to that present in a conventionally cast state of the same chemistry. The processing conditions leading to granule shape defects and causing surface oxidation did not affect their internal microstructure. The granules’ microstructures of fine equiaxed dendrites, while subjected to a sole external heat, transformed into thixotropic mixture of near spherical solid particles in a liquid matrix. It is suggested that microchemical and phase segregations are key factors which control granule melting behaviour. The dimensional and morphological features of the granules, as well as the internal microstructure, are beneficial for their potential application as a feedstock for thixo-molding.

Acknowledgements

The magnesium alloy particulates used in this research were manufactured at the experimental scale by Alberta Research Council, Edmonton, Alberta, Canada (G1, G3), Solikamsk Desulfurized Works, Solikamsk, Russia (G2), Phillips Plastics Co., Menomonie, Wisconsin, USA (G4), Intermag Technologies, Sainte-Foy, Que., Canada (G5).

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