Magnesium Alloy Strip Produced by Melt Conditioned Twin Roll Casting (MC-TRC) Process

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Abstract

Twin roll casting (TRC) offers a promising route for the economical production of Mg sheet but unfortunately, it produces strips with coarse and non-uniform microstructures and severe central line segregation. Recently, we have developed a melt conditioned twin roll casting (MC-TRC) process that, compared with the conventional TRC process, emphasizes solidification control at the casting stage rather than hot rolling. This is achieved by melt conditioning under intensive forced convention prior to twin roll casting and this results in enhanced heterogeneous nucleation followed by equiaxed growth and minimized central line segregation. In this paper we describe the MC-TRC process and compare the microstructures of Mg-alloy strip produced by the MC-TRC process with that of conventional TRC strip. Emphasis will be focused on the solidification behavior of the intensively sheared liquid metal and how this leads to microstructural refinement and compositional uniformity in the twin roll casting process.

Introduction

Magnesium is widely available as a natural resource [1, 2]. Magnesium sheet products offer a high-strength-to-weight ratio that makes them suitable for use in lightweight structural components. Magnesium alloys have limited deformability as they have hexagonal close packed (hcp) crystal structure which limits the number of slip systems available at room temperature [1, 3]. Wrought magnesium alloys are currently produced in far lower quantities than shape castings [4]. The annual growth rate of cast magnesium is likely to increase by approximately 15% for the next decade [5].

Normally, magnesium alloy sheet products are produced by a similar process to aluminum alloys, i.e. (i) direct chill casting into slabs; (ii) homogenization at about 480°C, and (iii) hot and/or cold rolling with frequent annealing steps. DC-cast Mg alloys are coarse-grained materials; rolling of magnesium alloys to sheet is expensive, time consuming with low metal yield [2, 6-11].

Twin roll casting (TRC) technology has been developed which produces Mg alloy strip directly from the melt to overcome the complications related to solid state deformation processing of Mg alloys and to reduce costs [2, 5, 7-14]. TRC combines casting and hot rolling into one step [2, 7, 15], and could provide homogeneity of microstructures, refined grain size, increased solid solubility and improved inclusion size distribution [12, 13]. However, in the conventional TRC there are issues with poor surface quality, low casting speed and severe segregation, and only a limited number of alloys are appropriate for strip production, [4, 15, 16].

MC-TRC (Melt Conditioned Twin Roll Casting) (Fig. 1) is a new process developed to overcome the disadvantages of the conventional TRC process, by conditioning liquid metal prior to solidification processing. This technology, developed at BCAST at Brunel University produces high quality strip by focusing on the control of solidification [16, 17]. Solidification control is achieved by a MCAST (Melt Conditioning by Advanced Shear Technology) unit which feeds a twin roll caster. The MCAST unit consists of a twin screw device, in which a pair of co-rotating, fully intermeshing and self-wiping screws is rotating at high speed inside a heated container with precise temperature control. The specially designed screws are able to provide high shear rate, high intensity of turbulence. The MCAST process provides conditioned melt with a uniform temperature, uniform chemical composition and well dispersed nucleating particles [19-22]. The conditioned melt is then supplied to a TRC machine operating at low applied load for the production of high quality thin strip. In this paper we present our experimental results on magnesium alloy strips produced by the MC-TRC process.

Experimental procedure

Magnesium alloy strips of AZ91D, AZ61 and AZ31 were manufactured by conventional and melt conditioned TRC. The chemical compositions of the alloys at different processing stages are presented in Table I. It shows that there was very little change in composition after melting and strip casting. A small lab-scale version of a TRC machine with a pair of steel rolls of 318 mm in diameter and 350 mm in width was used, which is capable of producing Mg-based alloy strips with different thicknesses (2-8 mm). In the present study, the casting speed was fixed at 2 revolutions per minute (rpm) and the roll gap was set at 3 mm.

Melting was performed in a steel crucible at 670-700°C and the melt was protected by 0.5% SF6 in N2. The alloy melts were transferred into the preheated header-box which was also under

![Figure 1. Schematic illustration of the melt conditioned twin roll casting (MC-TRC) process](image-url)
The protective atmosphere of 0.5% SF₆ in N₂.

The set up of the MCAST machine with the twin roll caster is shown schematically in Fig. 1. The liquid alloy was fed into the MCAST machine at 650°C under the protection of 0.5% SF₆ in N₂. The MCAST machine was operated at a temperature range between 590-650°C. The rotation speed of the twin-screw was varied between 500 and 800 revolutions per minute (rpm) and the shearing time between 30 and 120 s.

The samples for microstructural characterization were cut from the middle section of the both TRC and MC-TRC magnesium alloy strips in both longitudinal and transverse directions relative to the rolling direction.

The microstructure of the alloy was characterized by optical microscopy (OM), and scanning electron microscopy (SEM). The samples for OM and SEM were prepared by the standard technique of grinding and polishing, followed by etching in a 2 vol.-% Nital solution and Acetic-Picral, [1].

A Zeiss optical microscope was employed for the OM observations and the quantitative measurements, while a Jeol JXA840A scanning electron microscope, equipped with an energy dispersive spectroscopy (EDS) facility, was used to carry out the SEM examinations.

**Results**

**AZ91D TRC strip**

Fig. 2a. shows the microstructure of the entire cross-section of the AZ91D TRC strip in the longitudinal direction produced at a pouring temperature of 650°C. Fig. 2b. shows detailed information of the microstructure from the top to the bottom of the strip.

The microstructure of the TRC Mg-alloy strip is dominated by the growth of a columnar grain structure although a more equiaxed grain structure is noticeable in the central section. Significant central line (Fig. 2b-C) and surface segregation can also be observed in the TRC strip.

**Table I. Chemical composition of Mg-alloys**

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Processing stages</th>
<th>Chemical composition (in wt. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Zn</td>
</tr>
<tr>
<td>AZ91D</td>
<td>After melting</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>MC-TRC</td>
<td>0.72</td>
</tr>
<tr>
<td>AZ61</td>
<td>After melting</td>
<td>1.40</td>
</tr>
<tr>
<td></td>
<td>MC-TRC</td>
<td>1.38</td>
</tr>
<tr>
<td>AZ31</td>
<td>After melting</td>
<td>1.18</td>
</tr>
<tr>
<td></td>
<td>MC-TRC</td>
<td>0.97</td>
</tr>
</tbody>
</table>

**Figure 2. (a) Microstructure of the entire cross-section of TRC AZ91D strip along the longitudinal direction produced at a pouring temperature of 650°C, (b) (A-E) microstructural variation throughout the whole thickness direction from the top to the bottom.**

**Figure 3. SEM micrograph showing the central segregations in the TRC strip.**
Fig. 3 shows details of the segregation at the central region in the TRC strip. EDX compositional analysis shows that the composition at A and B in figure 3 are Mg-31.75%Al-4.30%Zn and Mg-19.68%Al-2.21%Zn-0.35%Mn, respectively.

The compositional variation (wt %) of Mg, Al and Zn through the strip thickness from the top surface to the bottom surface, are shown in Fig. 4a. Both Al and Zn contents are increased rapidly at centre line of the strip, showing severe chemical segregation in conventional TRC strip. (Fig. 2b-C)

The measured grain size through the strip thickness is shown in Fig. 4b. The TRC strip showed a significant variation of grain size between 200 and 750 µm through the thickness of the strip. In the columnar grain zone the dendrite sizes increased rapidly to about 600-750 µm. In the central equiaxed grain zone, the dendrite size decreased extensively to about 300µm

AZ91D, AZ61 and AZ31 MC-TRC strip

AZ91D MC-TRC strip. The whole cross-sectional microstructure of the MC-TRC AZ91D strip produced at shearing temperature of
603°C in the longitudinal direction is shown in Fig. 5a. No macro-segregations were observed throughout the entire sample. The A-B cross-section at higher magnification shows only equiaxed grains with uniform grain size (Fig. 5b).

The mean grain size throughout the thickness in longitudinal (LD) and transverse direction (TD) in the MC-TRC AZ91D strip was investigated in detail and the results are shown in Fig. 6a. The size of equiaxed grains is about 60~70 µm and is extremely uniform. No significant change is observed in grain size in both the longitudinal and transverse directions. The grain sizes of MC-TRC strip are about 10 times smaller than the grain size of TRC strip. The compositional variation throughout the thickness of the MC-TRC strip shows that there is no chemical segregation in the MC-TRC strip (Fig. 6b.), as confirmed by the SEM morphology of the central area of the MC-TRC strip (Fig. 7).

AZ61 and AZ31 MC-TRC strip. The longitudinal cross-sectional microstructures of the MC-TRC AZ61 and AZ31 strips at shearing temperature of 620°C and 635°C are shown in Fig. 8. Only very little segregations observed in both cases were comprised of small patches of liquid at the centre of the strip. As expected, in contrast to TRC, only the equiaxed grains were found no severe defects were observed in MC-TRC strips.

The mean grain size throughout the thickness in longitudinal (LD) and transverse direction (TD) in the MC-TRC AZ61 and AZ31 strips are shown in Fig. 9. The size of equiaxed grains is about 70~80 µm for both alloys and is extremely uniform. No significant difference is observed in the grain sizes from the TD and LD directions.

Discussion

In the conventional TRC process solidification of liquid melt occurs initially by the formation of columnar dendrites. This is due to the small number of nuclei available and the high temperature gradient between the roll surface and the alloy melt, resulting in a coarse and non-uniform microstructure. Under such solidification conditions dendritic cells proliferate resulting in enriched liquid at the growth front and eventually cause severe centerline defects.

AZ31

Figure 7. SEM micrograph showing the central region in the magnesium AZ91D MC-TRC strip.

Figure 8. Microstructure of MC-TRC AZ61 and AZ31 alloy strips at longitudinal direction.
In the MCAST process, the uniform temperature and uniform chemical composition of the conditioned alloy ensure a high nuclei survival rate. The intensive melt shearing disperses oxide particle clusters and breaks up oxide films (MgO) well-dispersed particles with a narrow size distribution. Such oxide particles are well wetted by the liquid alloy under the forced wetting conditions. As the solidification proceeds, these oxide particles may either act directly as nucleation sites for $\alpha$-Mg grains, or act as potent nucleation sites for intermetallic particles ($\text{Al}_8\text{Mn}_5$), which then nucleate the primary phase ($\alpha$-Mg). This produces a fine and fully equiaxed microstructure over the whole cross section of the MC-TRC strip. In this way melt conditioning is able to eliminate both the columnar grains and the macro-segregation present in the strip associated with the conventional TRC process.

Summary

A novel processing technology, the MC-TRC process, has been developed successfully to produce AZ91D, AZ61 and AZ31 magnesium alloy strips with high quality. Microstructure, chemical composition and grain size variation of the strip were studied. Extremely uniform composition and grain size were obtained throughout the whole MC-TRC strip. The mean grain size of the MC-TRC strips was about 80 $\mu$m. This work shows that the MC-TRC process can reduce considerably or eliminate defects such as the central line segregation present in conventional TRC strip.

References


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