Magnesium Technology 2012
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TMS (The Minerals, Metals & Materials Society), 2012

Magnesium Technology 2012

Casting and Solidification

Wednesday AM

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TWIN ROLL CASTING OF THIN AZ31 MAGNESIUM ALLOY STRIP WITH UNIFORM MICROSTRUCTURE AND CHEMISTRY

Iman Bayandorian, Ian Stone, Yan Huang, Zhongyun Fan

BCAST, Brunel University, Uxbridge, Middlesex, UB8 3PH, UK

Keywords: Twin roll casting, Magnesium alloys, Grain refinement, Melt conditioning

Abstract

Magnesium alloys produced by the existing twin roll casting (TRC) technique have coarse and non-uniform microstructures and severe centre-line segregation. Consequenty, TRC strip is cast typically no thinner than 5-9 mm, relying on costly subsequent downstream processing to produce thin strip with an improved microstructure. In the research described herein melt conditioning by intensive melt shearing was used prior to TRC to promote heterogeneous nucleation and provide a refined and uniform microstructure without severe macrosegregation. Additionally, a TRC machine with small diameter rolls was used to cast AZ31 strip of less than 2 mm in thickness suitable for direct component manufacturing such as stamping, without the necessity of hot rolling. The effects of process parameters, such as casting speed and melt superheat, on as-cast microstructure were studied. Experimental results show that the melt conditioning process provided considerable reduction in as-cast grain size and elimination of centre-line segregation. The texture and mechanical properties of melt conditioned strips were much improved over conventional TRC strips, offering the potential for higher quality final components.

Introduction

Wrought Mg alloys in sheet form are of great interest for applications in automotive, electronic packaging and other engineering disciplines, due to their low density, and high specific strength and stiffness. Twin roll casting (TRC), which was originally patented by Sir Henry Bessemer in 1865 [1], can produce magnesium alloy strip directly from the melt [2]. TRC offers a promising alternative route for producing Mg sheet products at high efficiency and low cost, with potentially improved microstructure and enhanced properties due to the high cooling rate compared with conventional ingot casting route [2]. However, the Mg strip produced by the current TRC technology has several problems including the predominance of coarse and non-uniform dendritic columnar grains and severe centre-line segregation, resulting in an increased burden on downstream processing and poor mechanical performance of the final products [2, 3]. Producing thicker strip by TRC followed by intensive downstream rolling operations, alloy development or adding grain refiners can help resolve these problems [4, 5]. As a result, however, the overall cost is increased and the products become less competitive.

The lack of ductility due to the non-uniformity of microstructure and centre-line segregation in TRC Mg strip is compounded by reduced sheet formability resulting from a strong basal texture which develops during lengthy downstream processing steps of annealing and repetitive hot/warm rolling. Significant effort is required to find a means to weaken the basal texture or obtain a random texture in Mg sheet. Non basal or weak textures have been reported recently in Mg alloys with additions of rare-earth elements such as Ce, Nd and Y [6]. However in addition to the high cost of such additions, insoluble particles may impair the mechanical properties and recyclability of the final Mg alloy product.

In contrast to the "chemical approach" to producing a fine grained microstructure by adding grain refiners, it is possible to employ a "physical approach" based on activating naturally occurring heterogeneous nucleant particles in the alloy melt by a physical means, such as intensive melt shearing by the MCAST (Melt Conditioning by Advanced Shearing Technology) process [7]. The MCAST process has been developed to manipulate or condition Mg and Al alloy melts prior to solidification processing, leading to significant grain refinement, considerable reduction of cast defects and substantial improvement of mechanical properties [7-9]. The combination of the MCAST process and a TRC machine (known as MC-TRC) takes full advantage of the TRC process for magnesium strip production whilst obtaining a uniform and refined microstructure, uniform chemistry and significantly improved mechanical properties [3]. The present work builds on the MC-TRC process with the ultimate aim of producing Mg strip sufficiently thin (less than 2mm) and formable for direct stamping of components without recourse to downstream rolling. In particular, this paper investigates the effect of casting parameters on the microstructure and texture development during MC-TRC of AZ31 Mg alloy.

Experimental Details

Commercial AZ31 alloy (Mg-3.34Al-0.97Zn-0.31Mn, wt.%), supplied by Magnesium Elektron (Manchester, UK) was melted in 10 kg batches in a steel crucible at 670 °C under a protective atmosphere. The alloy melt was then transferred to a twin screw MCAST unit and subjected to intensive shearing at ~640-650 °C for 60 s. The screw rotation speed was ~600 rpm, giving a shear rate of ~1633 s^{-1}. The conditioned melt was immediately fed, under a protective atmosphere, into either a horizontal TRC machine (HTRC) with 318 mm diameter rolls or a vertical TRC machine (VTRC) with smaller 100 mm diameter rolls. The strip thickness was controlled in the range of 1.5–6 mm and the casting speed was between 1 and 8 m/min. Downstream processing was carried out on some selected as-cast strips by homogenization at 400 °C, hot rolling (73%) at 400 °C and followed by annealing at 345 °C for 2 h. As a result of geometric considerations the smaller rolls in the VTRC process ensure that a narrower roll gap can be used. Thus thinner strip can be cast at higher speed.

Specimens for microstructure and texture characterization were cut from the middle of each strip along the casting or rolling direction and all examinations were carried out on the transverse section. Specimens for optical microscopy were prepared using standard metallographic procedures followed by etching in a solution of 5% HNO_3 in ethanol. Optical microscopy was performed on a Carl Zeiss Axioskop MAT 2 microscope equipped with Axiovision image analysis software. Specimens for electron backscatter diffraction (EBSD) were prepared by electropolishing in a solution of 15% nitric acid in ethanol at -30 °C was carried out for 30 s at 12 V. EBSD mapping was carried out on a Zeiss Supera35 FEGSEM equipped with an Oxford Instruments EBSD system. Tensile test samples with a gauge length of 25 mm were machined in accordance with the ASTM-E21 standard, and tested at room temperature and at a strain rate of 6.7×10^{-4} s^{-1} using a Lloyd EZ50 test frame.

Results and Discussion

The Effect of Melt Conditioning

Figure 1 shows typical optical micrographs of the microstructures of as-cast AZ31strip obtained by HTRC, VTRC and MC-VTRC. The microstructures formed without prior melt conditioning treatment (Figure 1a-d) consist of non-uniform, coarse, dendritic columnar grains with large, equiaxed grains in the centre and a

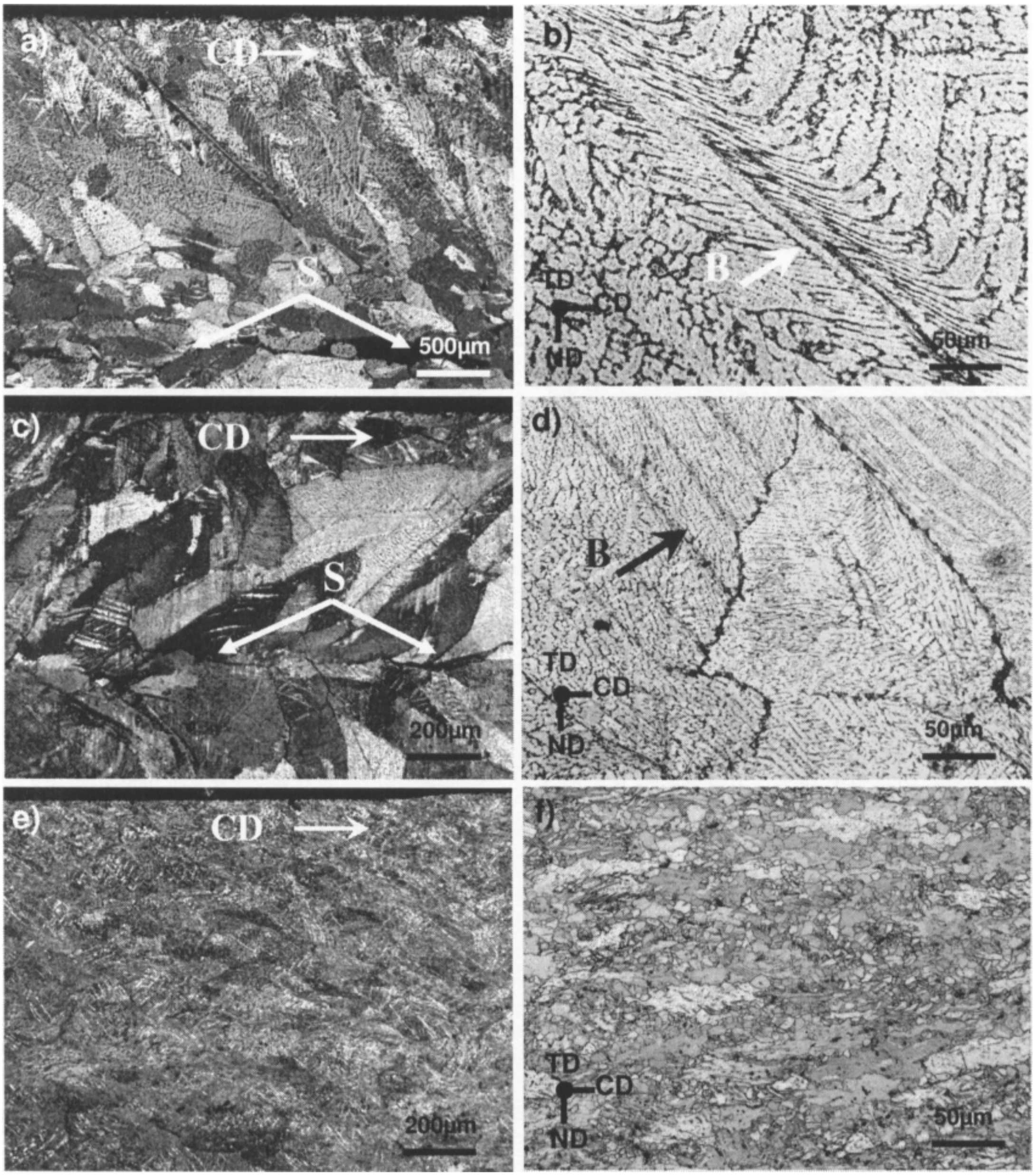

Figure 1. Optical micrographs showing long transverse section as-cast microstructures of AZ31 alloy strip produced by HTRC (a&b), VTRC (c&d) and MC-VTRC (e&f): pouring temperature of 640°C and casting speeds of (a&b) 1.35 m/min (thickness = 6 mm) and (c-f) 5 m/min (thickness = 1.8 mm). Severe chemical segregation (labelled 'S') along the centre-line of the two TRC strips (a-d) is clearly visible.

thin, fine grained chill layer at the surface. The HTRC (Figure 1a&b) and VTRC (Figure 1c&d) strips had grain sizes of ~616 µm and ~380 µm, respectively. In contrast, the MC-VTRC strip had fine ~50 µm sized grains necklaced by very fine recrystallized grains of ~7-9 µm in size (Figure 1e&f). Extensive microstructural examination revealed that the MC-VTRC strips were free from severe centre-line segregation, while macrosegregation (labelled 'S' in Figure 1) was found along most of the centre-line of the HTRC and VTRC strips due to directional crystal growth. These findings are in agreement with previous results published by the authors and other researchers [2, 3]. It has been shown previously that the intensive melt shearing offered by MCAST develops uniform temperature, uniform chemical composition and disperses evenly magnesium oxide films and oxide skins into individual MgO particles of 100-200 nm in diameter that act as potent nucleation sites [7, 8]. Therefore, heterogeneous nucleation during the solidification is enhanced due to the increased number of potential nucleating particles and increased nuclei survival rate, giving rise to the refined and uniform microstructure of the AZ31 strip produced by MC-VTRC. This equiaxed solidification process prohibited the accumulation of solute concentrated liquid in the central region, successfully eliminating the formation of centre-line segregation.

Dynamic recrystallization in Mg alloys accelerates increasingly under greater amounts of plastic deformation and larger numbers of existing grain boundaries (i.e. finer grains). Recent studies show that the increased amount of plastic deformation in the refined microstructure of MC-TRC strip generates higher stored energy in the material compared with TRC strip [10]. This was mainly responsible for the enhanced kinetics of dynamic recrystallization in the MC-VTRC as-cast AZ31 strip (Figure 1e&f). The plastic deformation in the HTRC and VTRC strips mainly occurred at the surface regions. In the coarse columnar dendrites, plastic deformation affects the structure by macroscopic shear banding (labelled B in Figure 1).

The Effect of Casting Parameters

So far, the results show that the application of melt conditioning by intensive melt shearing was necessary for obtaining twin roll cast AZ31 strip with a uniform microstructure and chemistry. However, the following results show that an optimised combination of casting parameters is also important for achieving the desirable microstructure.

Melt Superheat Figure 2 provides optical micrographs of MC-VTRC AZ31 strips cast with melt superheats of 18°C and 6°C (melt temperatures of 650 °C and 638 °C) respectively. Figure 2 shows that the 12°C difference in superheat has a significant effect on the microstructural characteristics of MC-VTRC strip. For the strip cast with 18°C superheat an equiaxed dendritic structure dominated, while for the strip cast with 6°C superheat a significant number of new grains formed due to dynamic recrystallization. At lower superheat less cooling is required during casting pushing the liquid/mushy sump towards the entry side of the rolls and so giving rise to a longer region of fully solid material within the rolls and thus a longer zone for plastic deformation. As a result, a greater number of dynamically recrystallized grains are generated for lower superheat. In addition, it is important to point out that intensive melt shearing enable TRC with low superheat. Without melt conditioning, the naturally occurring oxide films causes uneven feeding and possible blockage of the tip of the headbox, while melt conditioning can mitigate such problems by dispersing the oxide films into fine scale particles.

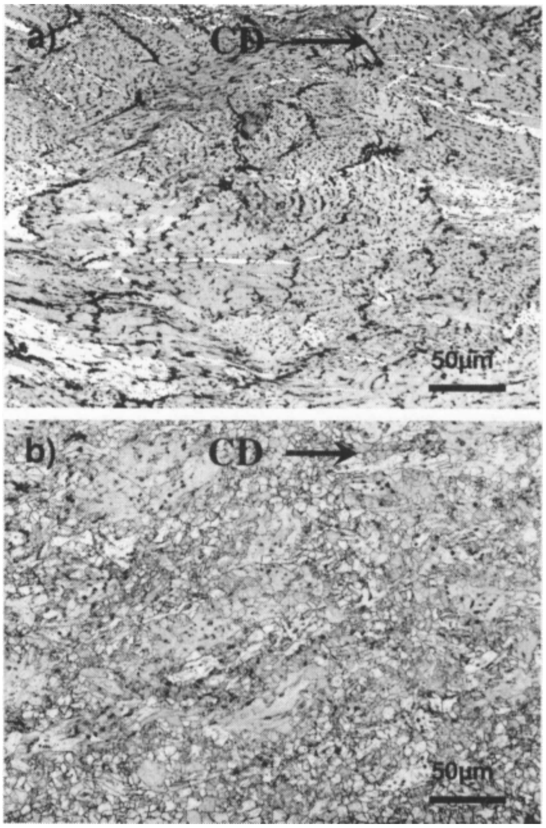

Figure 2. Optical micrographs of as-cast MC-VTRC AZ31 strips obtained at a casting speed of 5 m/min and pouring temperatures of (a) 650 °C and (b) 638 °C.

Casting speed Figure 3 illustrates the effect of different casting speeds (2.4-8m/min) on the microstructure of MC-VTRC strips. At 8m/min the microstructure is characterized by equiaxed dendritic grains (Figure 3a). At this very high casting speed solidification was uneven throughout the strip thickness, and some patches of liquid regions remained during the plastic deformation in the nip forming solute rich regions. Such patches manifest themselves in Figure 3a as intermetallic rich regions necklaced by particle stimulated recrystallized grains. At the reduced speeds of 4m/min and 2.4m/min, more extensive deformation features were apparent, such as shear bands, twins (labelled T) and a greater number of new recrystallized grains (labelled C), as shown in Figure 3b&c. With decreasing casting speed, the melt will have more time to release heat through the roll surfaces for a given distance from the tundish and therefore the liquid/mushy sump will be further towards the entry side of the rolls. As a result, the plastic deformation zone is lengthened and more plastic deformation is introduced to the solidifying strip, for a fixed gauge thickness and setback length.

Figure 4 shows the microstructures of MC-VTRC AZ31 strips produced at casting speeds of 5m/min and 8m/min and subsequently homogenized at 400 °C for 90 min. After homogenization, the strip cast at the lower speed developed a uniform and fine grain structure, with an average grain size of approximately 8 µm, whereas the strip cast at the higher speed developed a non-uniform structure of large and irregular

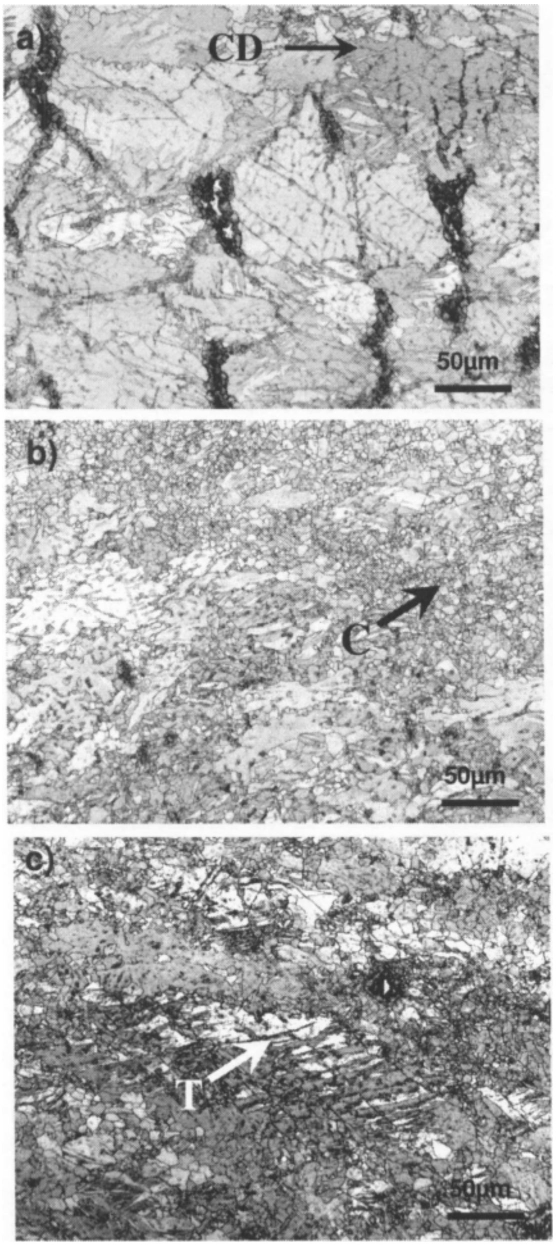

Figure 3. Optical micrographs of as-cast MC-VTRC AZ31 strips, obtained at a pouring temperature of 640 °C and casting speeds of (a) 8 m/min, (b) 4 m/min and (c) 2.4 m/min.

recrystallized and unrecrystallized grains. These results show that the enhancement of recrystallization during subsequent homogenization depends on the amount of energy stored in the material as a result of deformation during the casting stage.

Texture and Mechanical Properties

Figure 5 shows the microstructures and EBSD pole figures of conventional HTRC AZ31 strip (Figure 5a&c) which has undergone a lengthy downstream process of homogenization, rolling and annealing to provide a strip of 1.7mm thickness, and a homogenized MC-VTRC strip (Figure 5b&d) cast directly to a similar thickness of 1.8mm. The microstructure of homogenized MC-VTRC strip (Figure 5b) comprised uniformly very fine recrystallized grains while the homogenized, rolled and annealed HTRC strip (Figure 5a) had a non-uniform structure of fine recrystallized and coarse un-recrystallized grains. The corresponding EBSD pole figures showed that both strips had similar texture, dominated by the basal component (Figure 5c&d). However, the basal texture of the homogenized-only MC-VTRC strip was significantly weaker in intensity than that of the HTRC strip subjected to homogenization, hot rolling and annealing.

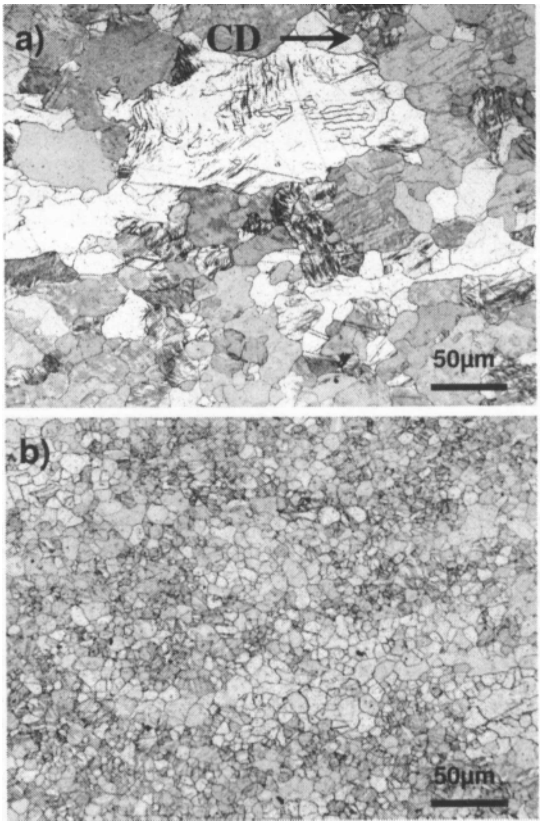

Figure 4. Optical micrographs homogenized (400 °C for 90 min) MC-VTRC AZ31 strips obtained at a pouring temperature of 640 °C and casting speeds of (a) 8 m/min and (b) 5 m/min.

The tensile mechanical properties of the homogenized, hot rolled and annealed HTRC AZ31 strip and the homogenized only MC-VTRC strip are presented in Table I. Compared with the highly processed HTRC strip, the homogenized-only MC-VTRC strip had a similar UTS and lower 0.2% proof stress which makes the MC-VTRC more suitable for further forming processes such as stamping. Moreover, the MC-VTRC strip had a remarkably high tensile elongation in comparison with the HTRC strip which enhances its suitability for forming still further. The enhanced tensile properties of the MC-VTRC strip cast directly to the final gauge compared with the conventional hot rolled HTRC strip are considered to be due to: (i) the more refined and uniform microstructure, (ii) the elimination of severe centre-line

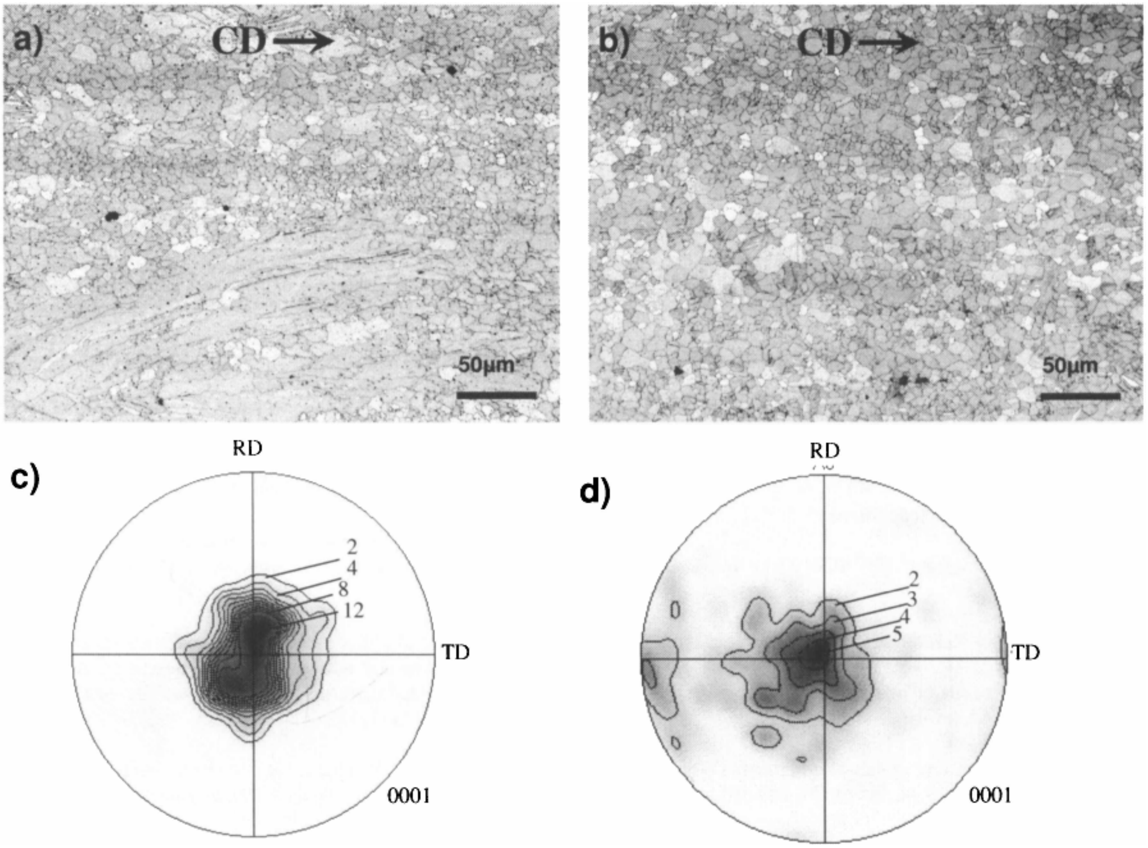

Figure 5. Optical micrographs of (a) conventional HTRC AZ31strip cast at 1.35 m/min (thickness = 6 mm) subsequently homogenized at 400 °C for 1 h, hot rolled at 400 °C to 73% (final thickness = 1.7 mm) and annealed at 345 °C for 2 h, and (b) MC-VTRC strip cast at 2.4 m/min (thickness = 1.8 mm) subsequently homogenized at 400 °C for 1 h; and (0001) EBSD pole figures (c) and (d) showing the textures corresponding to the microstructures in (a) and (b) respectively.

segregation (which remained in the TRC strips even after lengthy downstream processing) and (iii) the weaker basal texture. It has been shown that due to the brittleness and poor strength of the β-phase in AZ31, micro-cracks are likely to nucleate at the α-Mg/β interface and so particularly within the regions of centre-line segregation in conventional TRC strip [9]. Moreover, textures usually have a strong effect on the tensile deformation of wrought Mg alloys. In this work, the homogenized-only MC-VTRC thin strip has weaker basal texture which leads to lower yield stress and enhanced elongation compared with the highly processed TRC strip. The impact of MC-VTRC on the formability of Mg alloy sheet is the subject of ongoing investigation.

Table I. Room temperature tensile properties of the conventional HTRC strip after homogenization at 400 °C for 1 h, hot rolling at 400 °C to 73% and annealing at 345 °C for 2 h, and MC-VTRC strip after homogenization at 400 °C for 90 min.

Process	**Conditions**	**0.2% Proof (MPa)**	**UTS (MPa)**	**Uniform Elongation (%)**	**Elongation-to-failure (%)**
HTRC	Hom+Hot-rolled+Annealed (t^* = 6 » 1.7mm)	181.6	243.1	6.1	9.6
MC-VTRC	Hom (t^* = 1.8mm)	126.4	248.1	18.5	22.7

* Strip thickness (mm)

Conclusions

(1) The application of a vertical twin roll caster with small diameter rolls facilitates the production of very thin Mg alloy strip (less than 2 mm in thickness) at higher casting speeds and lower roll forces.

(2) Melt conditioning by intensive shearing prior to vertical twin roll casting of AZ31 Mg alloy resulted in strips with a fine and uniform microstructure free of centre-line segregation.

(3) It has been demonstrated that an optimised combination of small roll MC-TRC casting parameters and subsequent homogenization heat treatment made it possible to produce near final gauge AZ31 Mg alloy strips with significantly greater ductility than strips of similar gauge produced by conventional TRC and downstream thermomechanical processing.

Acknowledgement

The support of EPSRC (grant EP/H026177/1) is gratefully acknowledged.

References

1. H. Bessemer, "Improvement in the manufacture of iron and steel," *US Patent*, 1865, no. 49,053.
2. M. Ferry, *Direct strip casting of metals and alloys* (Woodhead Publishing Limited, Cambridge, 2006), 90, 189-191.
3. I. Bayandorian et al., "Magnesium alloy strip produced by melt conditioned twin roll casting (MC-TRC) process" (paper presented at the TMS 2009 Annual Meeting and Exhibition, Magnesium Technology, San Francisco, CA, USA, 2009), 363-368.
4. S.S. Park et al., "The twin-roll casting of magnesium alloys," *JOM*, 61 (2009), 14-18.
5. H. Chen et al., "Microstructure and mechanical properties of Mg–4.5Al–1.0Zn alloy sheets produced by twin roll casting and sequential warm rolling," *Mater Sci Eng A*, 492 (2008), 317-326.
6. K. Hantzsche et al., "Effect of rare earth additions on microstructure and texture development of magnesium alloy sheets," *Scripta Mater*, 63 (2010), 725-730.
7. H. Men, B. Jiang, and Z. Fan, "Mechanisms of grain refinement by intensive shearing of AZ91 alloy melt," *Acta Mater*, 58 (19) (2010), 6526-6534.
8. Z. Fan et al., "Enhanced heterogeneous nucleation in AZ91D alloy by intensive melt shearing," *Acta Mater*, 57 (16) (2009), 4891-4901.
9. S. Kumar et al., "Influence of intensive melt shearing on the microstructure and mechanical properties of an Al-Mg alloy with high added impurity content," *Metall and Mater Trans A*, 42 (2011), 3141-3149.
10. I. Bayandorian, Y. Huang, and Z. Fan, "Microstructures and mechanical properties of an AZ91 magnesium alloy processed by melt-conditioned twin roll casting and subsequent thermomechanical processing," *J Mater Sci Technol*, in press.